NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

THESIS

APPLICABILITY OF PERFORMANCE ASSESSMENT TOOLS TO MARINE CORPS AIR GROUND TASK FORCE C4 SYSTEM OF SYSTEMS PERFORMANCE ASSESSMENT

by

Michael O'Neil

September 2010

Thesis Advisor:	Gregory Miller
Second Reader:	David Rathgeber

Approved for public release; distribution is unlimited

THIS PAGE INTENTIONALLY LEFT BLANK

REPORT DOCUMENTATION PAGE		Form Approved OMB No. 0704-0188
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instruction, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188) Washington DC 20503.		
1. AGENCY USE ONLY *(Leave blank)*	**2. REPORT DATE** September 2010	**3. REPORT TYPE AND DATES COVERED** Master's Thesis
4. TITLE AND SUBTITLE Applicability of Performance Assessment Tools to Marine Corps Air Ground Task Force C4 System of Systems Performance Assessment		**5. FUNDING NUMBERS**
6. AUTHOR(S) Michael S. O'Neil		

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
    Naval Postgraduate School
    Monterey, CA 93943-5000
		8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING /MONITORING AGENCY NAME(S) AND ADDRESS(ES)
    Marine Corps Tactical Systems Support Activity
    Camp Pendleton, CA 92055
		10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government. IRB Protocol number _____.		
12a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution unlimited		**12b. DISTRIBUTION CODE** A

13. ABSTRACT (maximum 200 words)

This research focuses on the application of existing assessment tools that may be applicable to Marine Air Ground Task Force (MAGTF) Command, Control, Communications and Computers (C4) System of Systems (SoS) performance assessment efforts. An analysis of the Marine Corps Tactical Systems Support Activity's (MCTSSA's) C4 SoS assessment approach provides a means for defining a MAGTF C4 SoS and for illustrating how that SoS is represented in the assessment environment. This provides the framework and context for follow-on examination of SoS performance metrics.   The challenges with defining specific performance metrics and examination of past assessment events using those metrics provide the basis for discussion of alternative approaches and application of assessment tools specifically tailored for SoS assessment efforts. Three specific tools, i-Score, Interoperability Quotient (IQ), and Dynamic Software Architecture Visualization and Evaluation (DynSAVE), are examined. The results indicate i-Score and DynSAVE offer the greatest potential applicability to the MAGTF SoS assessment effort. In a culminating discussion, applying a multicriteria identification process to obtain a mathematical model that correlates an interoperability measure with measurable SoS performance criteria is proposed as a means of extending the i-Score model for greater applicability to SoS assessment and performance improvement efforts.

14. SUBJECT TERMS SoS, Interoperability, IQ, SAVE, i-Score, MAGTF			**15. NUMBER OF PAGES** 93
			16. PRICE CODE
17. SECURITY CLASSIFICATION OF REPORT Unclassified	**18. SECURITY CLASSIFICATION OF THIS PAGE** Unclassified	**19. SECURITY CLASSIFICATION OF ABSTRACT** Unclassified	**20. LIMITATION OF ABSTRACT** UU

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. 239-18

THIS PAGE INTENTIONALLY LEFT BLANK

APPLICABILITY OF PERFORMANCE ASSESSMENT TOOLS TO MARINE CORPS AIR GROUND TASK FORCE C4 SYSTEM OF SYSTEMS PERFORMANCE ASSESSMENT

Michael S. O'Neil
Major (Retired), United States Marine Corps
B.S., Virginia Military Institute, 1980
M.S., Naval Postgraduate School, 1993

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN SYSTEMS ENGINEERING MANAGEMENT

from the

**NAVAL POSTGRADUATE SCHOOL
September 2010**

Author: Michael O'Neil

Approved by: Gregory Miller
                 Thesis Advisor

                 Dr. David Rathgeber
                 Second Reader

                 Dr. Clifford Whitcomb
                 Chairman, Department of Systems Engineering

THIS PAGE INTENTIONALLY LEFT BLANK

ABSTRACT

This research focuses on the application of existing assessment tools that may be applicable to Marine Air Ground Task Force (MAGTF) Command, Control, Communications and Computers (C4) System of Systems (SoS) performance assessment efforts. An analysis of the Marine Corps Tactical Systems Support Activity's (MCTSSA's) C4 SoS assessment approach provides a means for defining a MAGTF C4 SoS and for illustrating how that SoS is represented in the assessment environment. This provides the framework and context for follow-on examination of SoS performance metrics. The challenges with defining specific performance metrics and examination of past assessment events using those metrics provide the basis for discussion of alternative approaches and application of assessment tools specifically tailored for SoS assessment efforts. Three specific tools, i-Score, Interoperability Quotient (IQ), and Dynamic Software Architecture Visualization and Evaluation (DynSAVE), are examined. The results indicate i-Score and DynSAVE offer the greatest potential applicability to the MAGTF SoS assessment effort. In a culminating discussion, applying a multicriteria identification process to obtain a mathematical model that correlates an interoperability measure with measurable SoS performance criteria is proposed as a means of extending the i-Score model for greater applicability to SoS assessment and performance improvement efforts.

THIS PAGE INTENTIONALLY LEFT BLANK

TABLE OF CONTENTS

LIST OF FIGURES

THIS PAGE INTENTIONALLY LEFT BLANK

LIST OF TABLES

THIS PAGE INTENTIONALLY LEFT BLANK

EXECUTIVE SUMMARY

Over a number of years, the Marine Corps Tactical Systems Support Activity has aggressively pursued new and innovative ways to improve efforts to assess the performance of tactical C4 Systems of Systems prior to deployment in an operational environment. In that pursuit, determining how best to approach performance assessments of large-scale, complex SoS has proven a challenge that extends beyond the Marine Corps to a fundamental system of systems engineering challenge shared by acquisition and test organizations and activities throughout the Department of Defense. Selecting key performance criteria, developing methodologies for conducting large-scale SoS assessments and defining more quantitative means for measuring and assessing SoS performance and behavior all serve as a central challenge and the genesis of this study.

After a high-level review of efforts to address the challenges associated with SoS assessments at both Joint and Marine Corps component level, three tools were examined for their applicability specifically to C4 SoS assessment efforts. While each tool provides a unique approach that may help better quantify the performance of a MAGTF C4 SoS, they are also very similar in that they each examine information exchanges at the component level to derive an overall SoS performance assessment measure in terms of interoperability. The tools examined included the i-Score methodology developed through the Air Force Institute of Technology, the Interoperability Quotient (IQ) methodology developed by Northrop Grumman Corporation and the Dynamic Software Architecture Visualization and Evaluation (DynSAVE) tool and process developed by the Fraunhofer Center for Experimental Software Engineering Maryland.

Of these tools, i-Score and DynSAVE offer the most potential for follow-on analysis, with the i-Score methodology providing a means for deriving a quantitative measure of SoS interoperability and the DynSAVE software tool providing a means of quantifying the anomalous behavior and relative efficiency of the SoS. A discussion of an approach to develop a mathematical model that correlates an interoperability measure with measurable SoS performance criteria using a multicriteria identification process serves as the culminating effort of this study. With a mature mathematical model and

high degree of confidence in the correlation between the performance criteria measure predicted by the interoperability model and the performance measure observed from the prototype, the mathematical model may provide a cost effective and rapid means to examine the SoS for potential performance improvement.

LIST OF ACRONYMS AND ABBREVIATIONS

– A –

ACE.....................Aviation Combat Element
AFIT ....Air Force Institute of Technology
AFATDS ....Advanced Field Artillery Tactical Data System
AT&L.................Acquisition Technology & Logistics

– C –

C2 ....Command and Control
C4 ....Command, Control, Communications, and Computers
CAC2S ....Common Aviation Command and Control System
CE.......................Command Element
COC....................Combat Operations Center
CPOF..................Command Post of the Future
CTM ....Capability Test Methodology

– D –

DAG ....Defense Acquisition Guide
DASC ....Direct Air Support Center
DAU ....Defense Acquisition University
DIS ....Distributed Interactive Simulation
DoD ....Department of Defense
DOT&E ....Director Operational Test & Evaluation
DynSAVE...........Dynamic Software Architecture Visualization and Evaluation

– F –

FAC.....................Forward Air Controller
FC-MD ....Fraunhofer Center for Experimental Software Engineering Maryland
FCS.....................Future Combat Systems
FEDOS ....Federation of Systems
FOC....................Full Operational Capability
FSCC ....Fire Support Coordination Center

– G –

GCE....................Ground Combat Element
GCSS ....Global Combat Support System

– H –

HCI.....................Human Computer Interface
HLA....................High-Level Architecture

– I –

IA........................Information Assurance
ICAS ....Immediate Close Air Support
ICD ....Interface Control Document
InterTEC.............Interoperability Test and Evaluation Capability
IOC ....Initial Operational Capability
IOW ....Intelligence Operations Workstation
IQ........................Interoperability Quotient

– J –

JADOCS.............Joint Automated Deep Operations Coordination System
JBD2...................Joint Battlespace Dynamic Deconfliction
JCIDS ....Joint Capabilities Integration and Development System
JITC ....Joint Interoperability Test Command
JMETC ....Joint Mission Environment Test Capability
JMT ....Joint Mission Threads
JNMS.................Joint Network Management Systems
JTEM ....Joint Test and Evaluation Methodology
JTEN..................Joint Training and Experimentation Network

– K –

KPP.....................Key Performance Parameter

I.   INTRODUCTION

A.   BACKGROUND

In warfare past and present, the pursuit of improved and more effective Command and Control (C2) on the battlefield has been, and is still, a relentless effort. As one of the Marine Corps' fundamental warfighting functions, C2 is unique in that it enables all the other warfighting functions: intelligence, maneuver, logistics, fires and force protection (U.S. Marine Corps, 2001). Through C2, these functions are executed with a coherency and purpose that results in an overall warfighting capability that is greater than the sum of the capabilities provided by the individual warfighting functions.

The proliferation of modern Command, Control, Communications and Computer (C4) systems and C4 system of systems (SoS) on the battlefield now serves as the focus of today's effort to improve the effectiveness of C2.   Advancements in technology and interoperability pursued and leveraged through C4 systems development efforts have contributed to unprecedented C2 capabilities, allowing once disparate systems to work together in a collaborative and synergistic manner that significantly enhances the ability of a commander to manage the battlespace.

However, at the same time, the advent of C4 systems has added a new dimension of complexity to the battlefield. The C4 systems and SoS are now an integral part of the battlespace, with the performance of the C4 SoS very much interconnected to the successful execution of the warfighting functions in pursuit of battlespace domination.

Furthermore, the dynamics of C4 SoS performance are in themselves complex and multidimensional. Changes to an individual subsystem in the SoS architecture may result in second- and third-order effects that result in degradation to the performance of the overall SoS that may be unrelated to the performance of the subsystem that has undergone change. To understand these complexities and to ensure that a modification to an existing C4 SoS architecture does not degrade overall performance of the SoS, the Marine Corps, for a number of years, has attempted to establish processes and procedures

for conducting C4 SoS assessment testing. However, while methodologies for testing individual systems are well documented and understood, there are a number of unique challenges associated with SoS assessment testing.

One of the most basic and critical challenges is determining appropriate testable performance measures for the SoS. While the individual systems that make up the SoS typically have well documented performance criteria that can be used as the basis for an assessment, in many cases the SoS may not. The challenge with determining appropriate performance measures in concert with many other complexities associated with SoS testing has resulted in testing approaches that differ very little from the methodology used to test the individual systems that constitute the SoS. That is to say, from a measurement and performance perspective, the individual systems in the SoS tend to serve as the focus of the test, which may not necessarily provide a complete or useful assessment of the SoS as a whole. This seems intuitive from the definition of a SoS "as a set or arrangement of systems that results from independent systems integrated into a larger system that delivers unique capabilities" (DAU, 2010). Those unique SoS capabilities imply unique attributes and behaviors derived from the arrangement and integration of the independent systems. These combined capabilities, attributes and behaviors uniquely characterize the SoS and imply that performance measures beyond the performance measures associated with the independent systems are needed to assess the SoS.

B.   PURPOSE

In the Office of the Under Secretary of Defense (Acquisition, Technology and Logistics) publication, *Systems Engineering Guide for Systems of Systems* (2008), a number of conditions are described that contribute to the challenges associated with Systems of Systems engineering. With Systems of Systems often comprised of individual systems in different stages of a very dynamic and often asynchronous acquisition life cycle management process and crossing many organizational management boundaries within the DoD and commercial industry, there is a need to expand and redefine systems engineering processes to accommodate these needs (Office of the Deputy Under Secretary of Defense for Acquisition and Technology [OSD], 2008):

Beyond these development challenges, depending on the complexity and distribution of the constituent systems, it may be infeasible or very difficult to completely test and evaluate SoS capabilities. (OSD, 2008, p. 13)

While the Department of Defense (DoD) and systems engineering community continue to refine and mature the processes for SoS engineering and development, the systems engineering testing community has struggled with defining how best to measure and assess the performance of the SoS. From that struggle, various test tools and test methodologies have been developed and demonstrated to address the test and evaluation challenge. This thesis investigates a small subset of existing assessment tools and analysis concepts that may be extended to the Marine Corps' C4 System of Systems assessment methodology as a means to obtain a more holistic assessment of the SoS under evaluation.

C.   RESEARCH QUESTIONS

Test and Evaluation (T&E) activities span the continuum of a disciplined systems engineering approach. As the engineering community attempts to understand and deal with the complexities of large-scale system of systems development efforts, the need to apply, adapt and modify T&E activities to accommodate a SoS engineering approach are evident. The following questions were designed to understand the challenges with SoS testing and opportunities for addressing those challenges through specific tools and analysis processes. While the questions are generic in nature, the intent is to address them in context with the specific challenges associated with the Marine Corps' approach to SoS assessment testing.

1. How can large-scale C4 System of Systems be tested and evaluated in a manner that reflects performance attributes associated with the System of Systems as a whole?

2. What are the key attributes of a C4 SoS that may serve as the basis for SoS level performance criteria?

3. What are some existing assessment tools and how may they be extended to aid in C4 SoS assessment process?

4. How might multicriteria identification improve or contribute to the Marine Corps' C4 SoS assessment methodology?

D. BENEFITS OF STUDY

As the Marine Corps continues to refine the processes and techniques for C4 system of systems assessment, other DoD organizations at both Joint and Component levels are doing the same. This thesis is intended to serve as a basis of knowledge that can be leveraged by the Marine Corps and other DoD test and evaluation activities, improving the use of assessment tools and analysis concepts to address the challenges associated with test and evaluation of large scale and complex C4 system of systems.

E. SCOPE AND METHODOLOGY

This thesis focuses on the application of existing assessment tools and analysis concepts that may be applicable to MAGTF C4 SoS performance assessment efforts. Data and documentation from past C4 SoS test events are used as well as input from the Marine Corps test and evaluation team planning future test events.

An analysis of the Marine Corps Tactical Systems Support Activity's (MCTSSA's) C4 SoS assessment approach, while serving in a lead role for the Marine Corps' SoS assessment effort, provides a means for defining a MAGTF C4 SoS and for illustrating how that SoS is represented in the assessment environment. This provides the framework and context for follow-on examination and discussion of performance metrics that are necessary for characterizing and ultimately assessing the performance of the SoS. The challenges with defining specific performance metrics and examination of past assessment events using those metrics provide the basis for discussion of alternative approaches and application of assessment tools specifically tailored for SoS assessment efforts.

Three specific tools are examined and viewed relative to their applicability to the MAGTF SoS assessment effort. The tools include i-Score, an Air Force Institute of Technology (AFIT) initiative to measure SoS interoperability; Interoperability Quotient (IQ), a commercial application demonstrated by the Navy to measure SoS performance;

and Software Architecture Visualization and Evaluation (SAVE), a toolset developed through the Fraunhofer Institute of Technology for optimizing and analyzing the architecture of implemented software systems.

Building on the examination of available analysis tools, an examination of how a Multicriteria Identification analysis concept may be applied to a MAGTF C4 SoS and extended as a means to improve SoS assessment testing is investigated. This culminates in an overall recommendation presented in the final chapter for improving C4 SoS assessments through appropriate use of assessment tools and analysis concepts. Overall methodology is depicted in Figure 1.
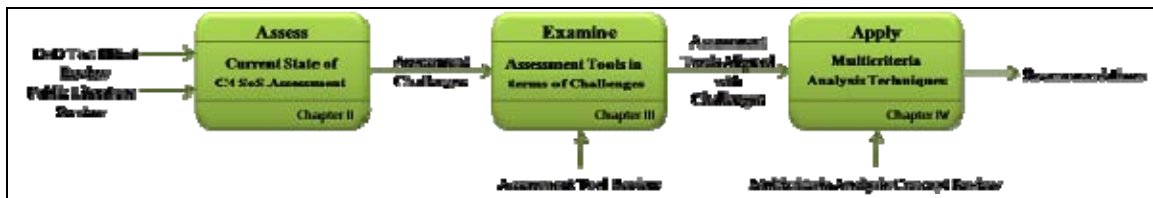

Figure 1.   Study Methodology.
Performance Tool Assessment Methodology
Process that guided this research.

THIS PAGE INTENTIONALLY LEFT BLANK

II.   MAGTF C4 SOS TEST AND EVALUATION PROGRAM REVIEW

A.   INTRODUCTION

The Marine Corps Systems Command (MCSC) serves as the Marine Corp's agent for acquisition and sustainment of systems and equipment. MCTSSA is a subordinate command within MCSC, providing engineering and technical services in support of MCSC's acquisition and sustainment role. Within the MCSC organization, MCTSSA falls under the cognizance of the Deputy Commander for Systems Engineering, Interoperability, Architectures & Technology (DC SIAT), who also serves as the Marine Corps' Technical Authority Deputy Warranting Officer. SIAT is chartered with providing "enterprise level system engineering across product lines and product life cycles to ensure MCSC provides end-to-end integrated, interoperable, and certified warfighting capabilities" (SIAT, 2010). In effect, SIAT serves as an agent for enabling horizontal integration across the MCSC product groups and systems development efforts. The resulting goal is to bring the individual systems together into a coherent, integrated system of systems architecture to provide warfighting capabilities.

In December 2006, the DC SIAT initiated an effort to develop a capability certification process to assess MCSC developed systems within a MAGTF SoS environment. MCTSSA, with a long history of supporting C4 systems throughout the acquisition life cycle, was tasked to develop the processes for assessing a MAGTF C4 SoS in support of the overall certification process for the MAGTF C2 capability.

Assessing a MAGTF C4 SoS was not new to MCTSSA. Previous attempts in the form of a Federation of Systems (FEDOS) test and evaluation program had met with mixed results. While FEDOS brought various C4 systems into a SoS environment for testing, no objective SoS-level performance requirements were established. With no established SoS-level performance requirements, the individual component systems in the SoS became the default focus of the test effort with performance metrics of the individual component systems in the SoS determined through negotiation with product sponsors. The product sponsors were suspect of the overall test results and questioned how the test

agency employed the individual system in the C4 architecture (logical and physical layout of the SoS test environment). Further, they failed to see value of a test that went beyond the scope of Developmental and Operational Test requirements as offered by Acosta et al. (2007):

> Further, FEDOS was perceived as a no-win situation for Product Groups. After a system had successfully passed Development and Operational Tests, and demonstrated compliance with system-level performance requirements as described in the Capability Development Document (CDD), Operational Requirements Document (ORD), or equivalent, FEDOS tested component systems in ways they had not been designed to be used. (Acosta et al., 2007, p. 29)

The Marine Corps' current SoS assessment effort that resulted from the 2006 directive from DC SIAT, termed MAGTF C4I Capabilities Certification (MC3). The MC3 effort is built upon the lessons learned from the FEDOS program and leverages efforts in the Joint test community looking to establish methods for executing tests of SoS in the Joint mission environment.

B. MAGTF C4 SOS DEFINED

Developing a common definition for a System of Systems (SoS) has been an evolving process and the subject of numerous discussion papers in industry and the DoD. In an IEEE International Conference on Systems of Systems Engineering 2009 article, John Clark provides a simple definition of a SoS as "The sum of the whole is greater than the sum of the individual parts" in which the parts are integrated and may or may not be members of a common domain (2009, p. 2).

In the DoD, this definition is expanded to accommodate considerations unique to the warfighting domain. The basic idea of the sum of the whole being greater that sum of the individual parts is still present, but the definition now also infers association with a warfighting capability. In the Chairman of the Joint Chiefs of Staff Instruction, CJCSI 3170.01F glossary, the SoS is defined as:

A set or arrangement of interdependent systems that are related or connected to provide a given capability. The loss of any part of the system could significantly degrade the performance or capabilities of the whole. The development of an SoS solution will involve trade space between the systems as well as within an individual system performance. (CJCS, 2007, p. GL-19)

This SoS definition is aligned with the Joint Capabilities Integration and Development System (JCIDS) that serves as an overarching process that guides the development of new capabilities for DoD Military Forces. JCIDS provides a methodology that is intended to improve the DoD acquisition process through a level of governance over the individual Service's acquisition efforts with a focus on identifying shortcomings and redundancy from a Joint warfighting capabilities perspective.

However, while JCIDS provides the acquisition community with a more holistic and SoS approach to the Joint acquisition process, the DoD Planning, Programming, Budgeting, and Execution (PPBE) process that guides acquisition funding and program management is not specifically structured to address the complexities of SoS acquisition efforts. That, along with internal acquisition community politics, legacy acquisition policies and many other factors has contributed to an acquisition approach that is focused on the individual system in terms of equipping the warfighter with a material solution supporting a needed capability. A system is engineered and developed to provide a function or capability within the context of being employed within a larger SoS (physical interfaces and data exchanges with other systems indentified and defined), but the SoS itself is more of a cooperative instantiation than an engineered entity.

However, as the definition and understanding of the SoS concept matures, the engineering focus in the acquisition process is beginning to transform. A new focus on SoS engineering takes systems engineering processes to the next level. In August 2008, The Director, Systems and Software Engineering Deputy Under Secretary of Defense (Acquisition and Technology) published Version 1 of the *Systems Engineering Guide for Systems of Systems*. Recognizing the growing interdependencies of systems to provide

warfighting capabilities, the guide serves as a first step to assist the systems engineering community with adapting systems engineering processes to systems of systems engineering needs (OSD, 2008).

The guide defines a SoS through reference to the 2008 DoD Defense Acquisition Guidebook (DAG), as "a set or arrangement of systems that results when independent and useful systems are integrated into a larger system that delivers unique capabilities" that remains unchanged in the 2010 update to the DAG. While this definition is not necessarily novel, the guide takes a step further by defining four types of SoS: Virtual, Collaborative, Acknowledged and Directed, as depicted in Table 1.

SoS Type	Description
Virtual	No central management authority or centrally agreed upon purpose for the SoS but displays large scale emergent behavior
Collaborative	Systems interact voluntarily to fill agreed upon central purpose
Acknowledged	Recognized objectives, designated manager and resources with individual systems retaining independent ownership, objectives, funding , development and sustainment
Directed	Integrated SoS built and centrally managed for a specific purpose with component systems retaining an ability to operate independently but with independent operational mode subordinated to SoS purpose

Table 1.   Types of SoS.
Definitions of different types of System of Systems as discussed in the 2008 *Systems Engineering Guide for Systems of Systems* (After: OSD, 2008, pp. 4–5).

The *Systems Engineering Guide for Systems of Systems* recognizes that most systems today are linked through net-centric information sharing to form a Virtual SoS. Collaborative SoS result as greater interdependencies are recognized and communities of interest are formed to work together for mutual benefit. Acknowledged SoS are becoming more predominant in DoD acquisition, demonstrating collaborative behavior, but with greater management authority and resources at the SoS level. Directed SoS are less predominant. The Army's Future Combat System (FCS) is offered as an example of

a Directed SoS, with individual systems development driven by the common objectives of the SoS (OSD, 2008). With budgetary and technology challenges that resulted in the cancellation of the FCS program in 2009, the Directed SoS may be the most challenging from an acquisition and management approach due to the inherent size and scope of a development effort at the Directed SoS level.

In the Marine Corps, the Combat Operations Center (COC) and the Common Aviation Command and Control System (CAC2S) are two programs of interest from a SoS perspective. The COC is a fielded program of record that provides the C2 facilities for the commander and staff of the four components of the MAGTF; Command Element (CE), Ground Combat Element (GCE), Air Combat Element (ACE), and Logistics Combat Element (LCE). The COC consists of physical components (tentage, power generation and environmental controls), Information technology infrastructure (servers and data storage), network and communications management capabilities (network management tools and interfaces for organic communications assets), and tactical software applications and associated computer platforms (PM MAGTF C2, 2009). While some of the component systems are unique to the COC, the C2-enabling capabilities are largely derived from components that are incorporated within the COC SoS but retain independent ownership, objectives, funding and sustainment.   The Advanced Field Artillery Tactical Data System (AFATDS), Command Post of the Future (CPOF), Joint Automated Deep Operations Coordination System (JADOCS) and Global Combat Support System (GCSS) are a few examples of systems that are part of the COC baseline configuration but are managed as independent programs.   Further, the wide-band communications infrastructure necessary to interface and tie individual COC together is also comprised of separately managed independent programs. Based on that, the COC, as seen in Figure 2, would most closely represent an Acknowledged SoS.
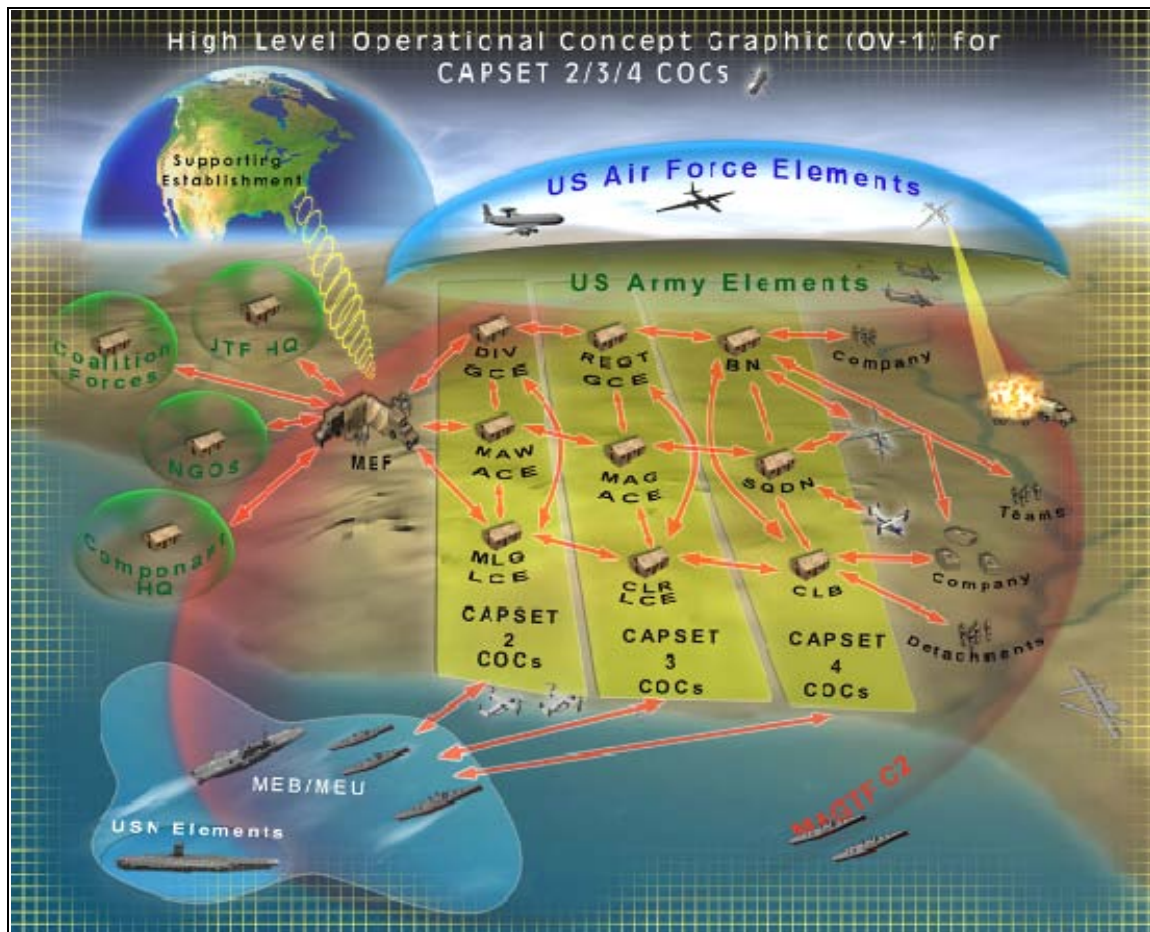
Figure 2.   Combat Operations Center (COC) OV-1.
The COC provides C2 facilities for the components of the MAGTF
(From: Zapata, 2010a).

The Marine Corps CAC2S program depicted in Figure 3 represents a more ambitious approach. The initial effort focused on a complete replacement for C2 equipment of the Marine Air Command and Control System (MACCS). With an intent to replace legacy single-mission systems with an integrated hardware and software solution for more effective command, control and coordination of air operations, this effort was most closely aligned with a Directed SoS development approach. However, much like FCS, CAC2S faced program management and technical challenges that required the program to restructure in 2009. With that restructure, CAC2S is now linked to the COC program, leveraging the C2 capabilities provided by the COC to meet some

of the C2 needs of the MACCS mission. Subsequently, with that dependency on another SoS, CAC2S would now also be considered an Acknowledged SoS.

Figure 3.　　Common Aviation Command and Control System (CAC2S) OV-1. The CAC2S represents an incremental SoS development effort that will replace the current Marine Air Command and Control System. In Increment I, Phase I, the functionality of the Direct Air Support Center (DASC) is replaced by CAC2S (From: Zapata, 2010b).

In the Draft 7 January 2010 *Mission Area "Systems of Systems" Systems Engineering Guidebook*, the concept of mission capability is reinforced:

> In the future, global operations will be conducted by distributed, integrated and interoperable forces. This future warfare is about capability delivered by 'System of Systems' operating as a single system. System of Systems (SoS) is defined in this document as a force package of interoperable platforms and nodes acting as a single system to achieve a mission capability, i.e. a mission level SoS. Typical characteristics include a high degree of collaboration and coordination, flexible addition or removal of component systems, and a net-centric architecture. The capabilities provided by each constituent system operating within the SoS are framed by the integrated force package architecture. (Chief Systems Engineer, 2010, p. 1)

For the Marine Corps, the MAGTF serves as the foundational structure that provides a unique combined arms air-ground warfighting capability. As depicted in Figure 4, each MAGTF is comprised of four core elements: the Command Element (CE) that provides for the overarching command of the MAGTF; the Ground Combat Element (GCE) with infantry, artillery and armor; the Aviation Combat Element (ACE) with fixed wing, rotary wing and aviation command and control; and the Logistics Combat Element (LCE) with supply, combat engineers, medical and other combat services capabilities. The basic premise is that this structure provides a mission capability that is greater than the sum of the individual components: the very essence of a SoS.
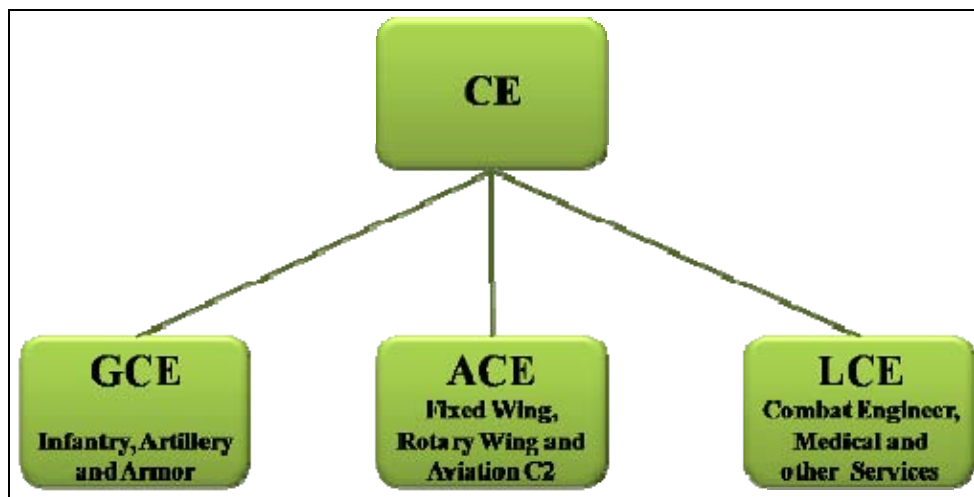
Figure 4.   MAGTF Components.
Graphical representation of MAGTF hierarchical structure.

While every MAGTF retains this basic structure, the size and individual component structure of the MAGTF is mission dependent and can range from largest—Marine Expeditionary Force (MEF) level (approximately 45,000 personnel)—to the smallest, Marine Expeditionary Unit (MEU) level (approximately 2,500 personnel). Both COC and CAC2S support this dynamic structure through modular and scalable design. The COC in particular is fielded in five different capability sets that are equated to an echelon of command; MEF COC (Capability Set I), Division COC (Capability Set II), Regimental COC (Capability Set III), Battalion COC (Capability Set IV) and Company COC (Capability Set V). A MEF level MAGTF with a MEF headquarters, Marine Division, Marine Aircraft Wing and Logistics Support Group would then consist

of multiple COCs in all five Capability Set variants. The CAC2S is fielded in a similar scalable manner with four different variations to accommodate C2 requirements for specific MACCS functions at Wing, Squadron, Echelon and Sub-Agency levels.

From a warfighting capability perspective, we can view the MAGTF and all its people, processes and technology as an independent SoS, fully capable of executing warfighting mission capabilities in support of defined operational objectives. The MAGTF SoS can also be considered an element of larger Joint SoS when employed as part of a Joint Task Force.

MAGTF C4 can be considered a SoS (within context of the greater MAGTF SoS) that is specifically architected to deliver a C2 capability in support of the C2 warfighting function. MAGTF C4 as a SoS is comprised of people (C4 operators and maintainers), processes (guided by doctrine and written procedures) and technology (communications systems, networking systems and C2 applications) that are brought together through an integrated MAGTF architecture that enable unique C2 functions and capabilities that cannot be achieved individually. Both COC and CAC2S (or currently MACCS) SoS, are components of the larger MAGTF C4 SoS, and together comprise a significant part of the MAGTF C4 SoS, with the intent of providing C2 capabilities at all echelons of command down through the Company level.

This is precisely the concept that is presented in the Marine Corps' MAGTF C2 vision. In 2008, a MAGTF C2 Transition Task Force was established to provide governance and oversight to the process of developing and fielding systems that support C2 capability. With the intent of harmonizing the development and fielding of C2 programs of record like CAC2S, COC and many others to deliver an end-to-end integrated C2 solution, this effort provides the Marine Corps with a means for transitioning from an Acknowledged to a more Directed SoS. Cloninger (2009) describes the mid-term goal of MAGTF C2 as an integrated SoS:

> MAGTF C2 will become an integrated C2 solution that will migrate the current multiplicity of stove-piped, disparate systems into an integrated system-of-systems that will support deployed aspects of Marine Corps C2 requirements from pre-deployment planning to execution and redeployment via multi-functional C2 nodes. (p. 103)

15

From this perspective, MAGTF C2 is seen as the end state of the transition of MAGTF C4 SoS from an Acknowledged to a MAGTF C2 Directed SoS. However, until that end-state is achieved, the MAGTF C4 SoS (as depicted in Figure 5) then is considered an Acknowledged SoS, comprised of both SoS and individual systems centrally employed and managed through the MAGTF (as a hierarchical organization) with a recognized objective to provide a C2 capability that maximizes combat capability through unity of effort.
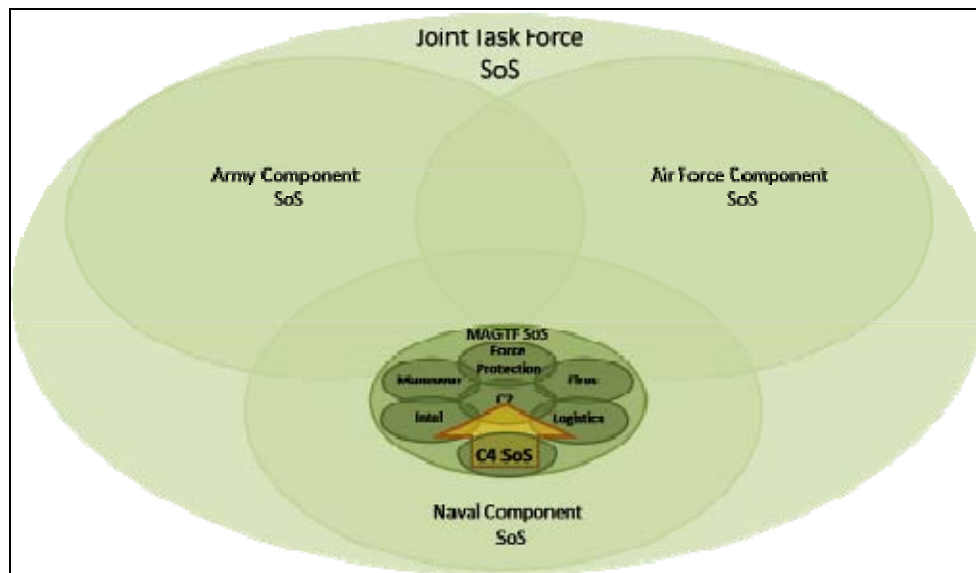
Figure 5.   MAGTF C4 SoS.
The MAGTF C4 SoS provides a C2 capability to the MAGTF SoS that in concert with the Army and Air Force Component SoS make up the Joint Task Force SoS.

C.   JOINT LEVEL SOS TEST AND EVALUATION APPROACH

While individual systems development with associated developmental test and operational test and evaluation (OT&E) is still the predominant focus in the DoD acquisition community, the reality of net-centric SoS warfare and the relevance of SoS performance to the ability to achieve mission capabilities have not gone unaddressed. Significant efforts, both individual and collaborative, to test, measure and quantify the performance of complex SoS have been, and continue to be, a major focus of both Component and Joint DoD testing organizations. At the Joint level, this effort has

predominantly fallen under the purview of the Under Secretary of Defense / Acquisition Technology & Logistics (AT&L) and Director Operational Test & Evaluation (DOT&E).

AT&L established the Joint Mission Environment Test Capability (JMETC) in 2006 to provide the infrastructure and common environment for distributed Live, Virtual and Constructive (LVC) testing in the Joint DoD community. JMETC enables distributed facilities to link together through the existing DoD Secure Defense Research and Engineering Network (SDREN) to provide a Joint environment in support of "Developmental testing, Operational Testing, Interoperability Certification, Net-Ready Key Performance Parameters (KPP) compliance testing, and Joint Mission Capability Portfolio Testing" (Lockhart & Ferguson, 2008, p. 161). JMETC offers a corporate approach to Joint testing, providing readily available connectivity over existing DoD networks, a common middleware for connecting distributed facilities, data exchange standards, data management, reuse repository and a suite of test tools for test planning, execution and analysis as described by (Lockhart & Ferguson, 2008):

- Connectivity. The Secure Defense Research and Engineering Network (SDREN) provides connectivity between test facilities. Training facilities can also be linked through the Joint Training and Experimentation Network (JTEN).

- Middleware. The Test and Training Enabling Architecture (TENA) serves as common data exchange environment used by distributed facilities to send and receive data. TENA provides gateways to connect to other data exchange protocols to include Distributed Interactive Simulation (DIS) and High-Level Architecture (HLA).

- Data Exchange Standards. Through TENA Object Models, a common language is provided for data exchange between systems in the distributed architecture.

- Data Management. JMETC provides a capability to archive test data from multiple facilities for analyses and evaluation of test results.

- Reuse Repository. A Web portal provides a means to share object models, middleware, software tools and documentation across the user community.

- Test Tools. A common suite of test tools is provided for planning, configuration, monitoring, control and analysis. The Interoperability Test and Evaluation Capability (InterTEC) is a secondary initiative under AT&L that started as a joint effort between the Joint Interoperability Test Command (JITC) and Naval Air Warfare Center (NAVAIR) and is now an integral part of JMETC and synonymous with the common test tool suite. From the JITC Web site, the InterTEC tool suite also provides the synthetic battlespace environment that shapes the test scenario through many-on-few scenario simulations and a simulation/emulation gateway to stimulate system sensors in the systems under test ("JITC," 2009).

In an effort complimentary to JMETC's Joint test infrastructure and common LVC test environment, the DOT&E Joint Test (JTEM) effort was chartered in 2006 for three years, to develop, test and evaluate methods and processes for conducting LVC Joint test events. The principal product that resulted from this effort was the JTEM Capability Test Methodology (CTM) that provides a framework for a capabilities-based approach for testing in a Joint mission environment. CTM version 2.0 describes a six-step methodology, consisting of 14 JTEM processes, as depicted in Figure 6.
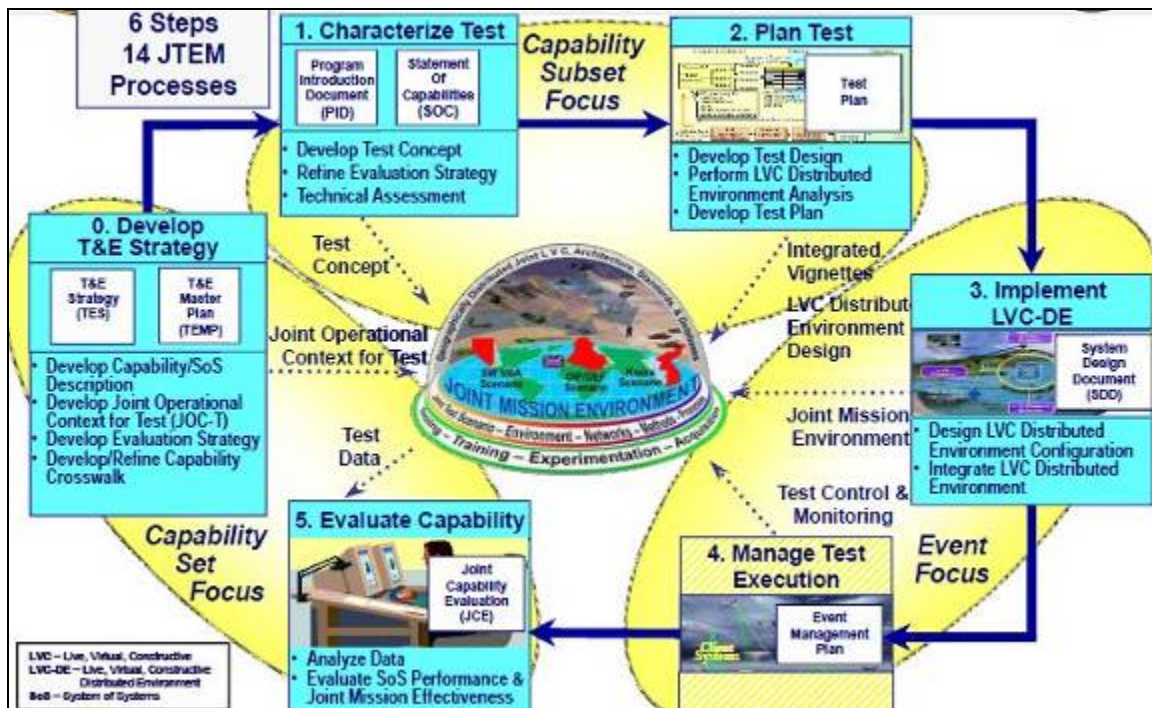
Figure 6.   JTEM CTMv2.0.
The six-step JTEM Capability Test Methodology offers a structured approach for
conducting an SoS assessment (From: Fiebrandt & Dryer, 2009, p. 3).

The six steps of the CTM provide a basic framework for any SoS evaluation.
Outlined in JTEM's *Action Officer's Handbook for Testing in a Joint Environment*
(Lorenzo, 2009), the CTM steps include:

- Develop T&E Strategy. This step was added in CTMv2.0 to address a critical
  first step to define the overall SoS evaluation strategy. The key aspects of this
  step are to define the SoS in terms of capability and define the operational
  context for SoS employment.

- Characterize Test. Once the SoS is defined, determining what aspects or
  attributes of the SoS can and should be measured to assess the SoS
  performance is a second key step. Without defined SoS measures of
  performance (typical of a non-Directed SoS), this can present the most
  challenging aspect of the methodology.

19

- Plan Test. The test plan that results from this step documents the overall test strategy, test design, and data collection methodology that guides test execution.

- Implement LVC Distributed Environment. JMETC facilitates implementation of the LVC distributed environment.

- Manage Test Execution. The InterTEC tool suite facilitates test management and execution.

- Evaluate Capability. The InterTEC tool suite facilitates data collection across the LVC distributed environment, however the significance of the evaluation is largely dependent on how well the performance measures were defined in the second step.

In 2008, JTEM demonstrated CTM version 2.0 in the FCS Joint Battlespace Dynamic Deconfliction (JBD2) test event. The event provided an opportunity for both JTEM and JMETC to mature their products and offered FCS an opportunity to conduct a complex SoS test event in support of an acquisition Milestone C decision. Hutchison, Lorenzo and Bryan (2009) describe the complexity of the event:

> To achieve these goals, JBD2 established a complex joint mission environment composed of 16 test sites and more than 40 unique live, virtual, and constructive systems connected across four time zones. These test sites represented all four Services and the U.S. Joint Forces Command. Of these 16 JBD2 sites, 10 were reused from two previous test venues that were a part of a series of events culminating in JBD2. Seven Service and joint initiatives were included as part of the test architecture. JBD2 truly provided joint context and stressed the boundaries of a live, virtual, and constructive joint mission environment. (p. 32)

For the FCS JBC2 event, the SoS under test provided a C2 capability that was focused on two factors:

- Battlespace Management Capability. Test to determine whether there was a difference between current and future SoS implementation during execution of mission tasks during the mission-based test scenario.

- <u>Timeliness of C2 processes</u>. Test to determine difference between current procedural-based processes versus future expedited-based processes (LeSueru, Millich & Stokes, 2009).

Of significance is that this event demonstrated test and evaluation of both material (SoS physical configuration with respect to battlespace management capability) and non-material (C2 processes) aspects of the SoS. Also relevant is the use of a complex, but operationally realistic mission scenario as depicted in Figure 7, which provided the basis for stressing the SoS under test.
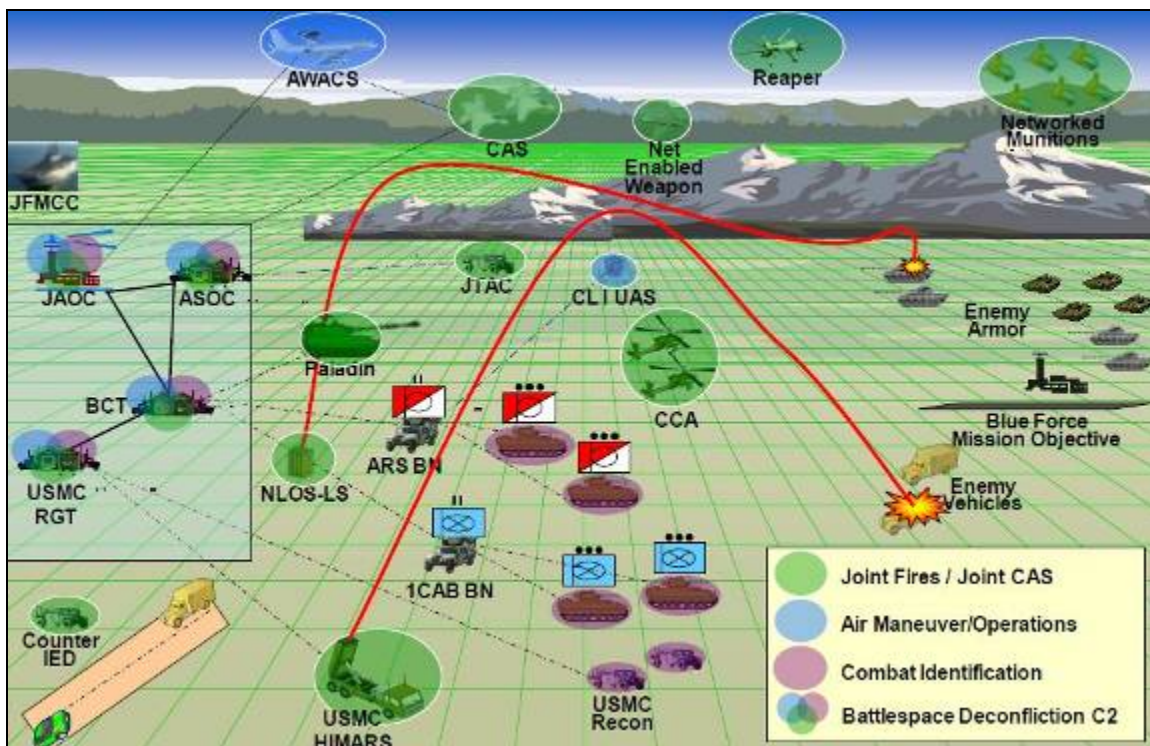
Figure 7.   JBD2 Operational View.
Operationally realistic mission thread from Joint Battlespace Dynamic Deconfliction Test Event (From: LeSueru, Millich & Stokes, 2009, p. 3).

D.   COMPONENT (MARINE CORPS) SOS TEST & EVALUATION APPROACH

At the Component level, the Marine Corps has taken a similar approach in both past (FEDOS) and current (MC3) SoS assessment efforts. Both efforts employed a

structured, process driven methodology and both were conducted in a test environment that attempted to replicate a MAGTF C4 SoS architecture. Although developed prior to and independent of JTEM, initial meeting with the JTEM program manager in January 2007 revealed significant parallels in approach and methodology:

- SoS capability-based assessment approach

- SoS architecture defined and rooted in individual systems' JCIDS artifacts (Operational Views and System Views)

- Operational scenario and mission tasks provide basis for evaluating the performance of the SoS

- Employed distributed test architecture with centralized test control

The significant similarities in methodology for SoS testing at the Joint level to the methodology developed by MCTSSA for SoS testing at the Component level, indicated potential for mutual benefit through continued collaboration. In October 2007, MCTSSA joined the JMETC community and began participation in JMETC test events as the Marine Corp component (MAGTF node) in the Joint test architecture. This served as an opportunity for the Marine Corps to further mature its SoS assessment methodology and leverage the capabilities provided by the JMETC InterTEC tool suite. The collaboration also highlighted a number of shared challenges: specifically the development of meaningful test threads, selection of SoS performance metrics and development of a comprehensive and consistent manner for characterizing the results of the SoS performance assessment.

E.   GAP ANALYSIS (ASSESSMENT ISSUES AND DEFICIENCIES)

The three shared challenges associated with SoS assessment (test threads, performance metrics and assessment reporting) are closely interrelated and improvements in one area could potentially yield improvement in the other areas. From a Component (MAGTF C4 SoS) perspective, a more detailed discussion of these challenges follows.

1. Operational Test Thread Concept

A central feature of the Marine Corps' C4 SoS testing methodology is the use of MAGTF-based capability mission tasks executed in an operational scenario. Translating the mission tasks to an operationally relevant test thread has been a challenge for a number of reasons:

- Each MAGTF is unique. While each MAGTF consists of the same core elements (CE, GCE, ACE and LCE), the size and specific component make up varies as dictated by Mission requirements.

- Each MAGTF C4 architecture is unique. Implementation of the C4 components in the MAGTF architecture to provide the C2 capability, though guided by doctrine and best practices, is left to the discretion of the MAGTF commander.

- Execution of mission tasks can vary. Mission tasks are well defined but how individual C4 components are used in concert with the execution of the tasks is often not defined.

All these factors come into play during the development of a test thread that replicates execution of a mission task in the test environment. Assumptions to accommodate all these factors are required as the test agency translates the mission tasks into a form that can be executed in the test scenario: mission task translated to test thread. Once developed, the abstracted test thread must then be validated to ensure it is still operationally relevant. During the C4 SoS assessment, significant resources (personnel and equipment) may be required to execute the test thread depending on degree of human to machine interaction necessary to complete the mission task.

To provide a true representation of the MAGTF C4 SoS in an operational context, a variety of mission tasks running in parallel and at various stages of completion are required. Multiple mission tasks, executed in concert with a defined MAGTF battle rhythm, would provide a meaningful context for assessing the performance of the C4 SoS. However, the effort and resources required to develop, validate and execute sufficient test threads to represent this is considerable and possibly infeasible without the

aid of modeling and simulation. Further, even with the MAGTF C4 SoS well defined and stressed through execution of realistic mission tasks, determining what to measure from a C4 SoS performance perspective, is still an issue without documented mission-task performance metrics to test against.

2. SoS Performance Metrics

In response to the lack of defined mission task performance metrics, the Marine Corps' 2007 MC3 MAGTF C4 SoS effort developed a unique metrics model in collaboration with stakeholders within the Marine Corps Combat Development Command (MCCDC), SIAT, MCTSSA, Marine Corps Operational Test and Evaluation Agency (MCOTEA) and Space and Naval Warfare (SPAWAR) Systems Center, Atlantic. The metrics model was intended to focus on characterizing the performance of the SoS in terms of mission-based test thread execution, vice performance of individual C4 systems and was comprised of five areas of measurement:

- Operator Complexity. Measure of level of difficulty to execute a test thread from a user's perspective. The measure was based on the total number of operator steps required at each system or node in the SoS during execution of the test thread.

- System Timeliness. Measure of total system time to execute the test thread. This measure was based on total digital transmission time and system processing time at each system or node in the SoS during execution of the test thread.

- System Accuracy. Measure of application layer accuracy as indicated by percent completion of digital messages between each system and node in the SoS during execution of the test thread.

- System Reliability. Measure of number of failures at each system or node in the SoS during execution of the test thread.

- Anomalous Behavior. Not a measure but a means to capture emergent or unexpected behavior within the SoS during execution of the test thread.

Although successfully demonstrated in a final test event, the value of the model was limited. While the intent was to establish a metrics model that focused on SoS level mission thread execution, the resulting SoS performance assessment was extrapolated from the performance of the individual systems in terms of the metrics as they completed tasks during execution of the test thread. Based on the author's personal observations and involvement with the 2007 test event, this shifted focus away from the SoS performance to a study of performance of individual systems operating within a SoS.

The MAGTF C2 working group provided another metrics model. In the MAGTF C2 Test and Evaluation Master Plan for 2010, five Critical Operational Issues (COIs) are defined that guide the selection of Key Performance Parameters (KPPs) with associated Measures of Performance (MOPs):

1. To what level does MAGTF C2 enable Blue Force Tracking of friendly assets?

2. To what level does MAGTF C2 provide force and unit commanders a Common Tactical Picture / Common Operational Picture?

3. To what level does MAGTF C2 provide adequate Situational Awareness to unit commanders and their forces?

4. To what level does the MAGTF C2 provide planning and collaborative functionality in the net-centric, service-oriented environment to distributed COCs?

5. To what level does MAGTF C2 provide the capability to communicate while on the move? (MAGTF C2, 2008, pp. 21–23)

Because the MAGTF C2 effort is primarily an SoS engineering oversight effort for a number of existing programs of record (CAC2S and COC serving as the primary programs of record), the KPPS and MOPs associated with COIs' 1,2,3 and 5 were extracted from the existing programs of record Capability Development Documents (MAGTF C2, 2008). COI 4 required creation of new MOPs aligned with the Net-Ready KPP defined in CJCSI 6212.01E. The Joint Interoperability Test Command (JITC) is responsible for conducting interoperability evaluations of programs of record to certify compliance with the five elements of the NR-KPP:

1. Compliant solution architecture: technical exchange of information and end-to-end use of that exchange.

2. Compliance with net-centric data and services strategies; evaluation of net-centric data and services to determine if net-ready.

3. Compliance with applicable GIG Technical Guidance (GTG).

4. Compliance with DOD Information Assurance (IA) requirements

5. Compliance with supportability requirements to include spectrum utilization and information bandwidth requirements, Selective Availability Anti-Spoofing Module (SAASM) and the Joint Tactical Radio System (JTRS), as applicable. (CJCSI 6212.01E, 2008, p. A-2)

For the MAGTF C2 effort, the NR-KPP certification requirements for the individual programs of record within the SoS (including COC and CAC2S) were adapted to address NR-KPP compliance from a SoS perspective. This methodology differs significantly from the approach taken in MC3. While MC3 attempts to characterize the performance of the SoS in terms of mission thread execution (warfighting capability), the MAGTF C2 approach is more oriented towards assessing the C2 capability provided by the SoS.

3. Reporting SoS Performance Results

To characterize and quantify the performance of the C4 SoS, MCTSSA's MC3 effort applied a risk-based reporting methodology. During the assessment event, mission-based test threads were executed through the C4 SoS and data was collected based on the established areas of measurement defined for the event (operator complexity, system timeliness, system accuracy, system reliability and anomalous behavior). The data was summarized and evaluated by a panel of stakeholders and experts to derive an overall risk score associated with executing the test thread in the C4 SoS. The overall results of the assessment effort were reported in a standard 5x5 risk chart in a manner similar to that depicted in Figure 8.
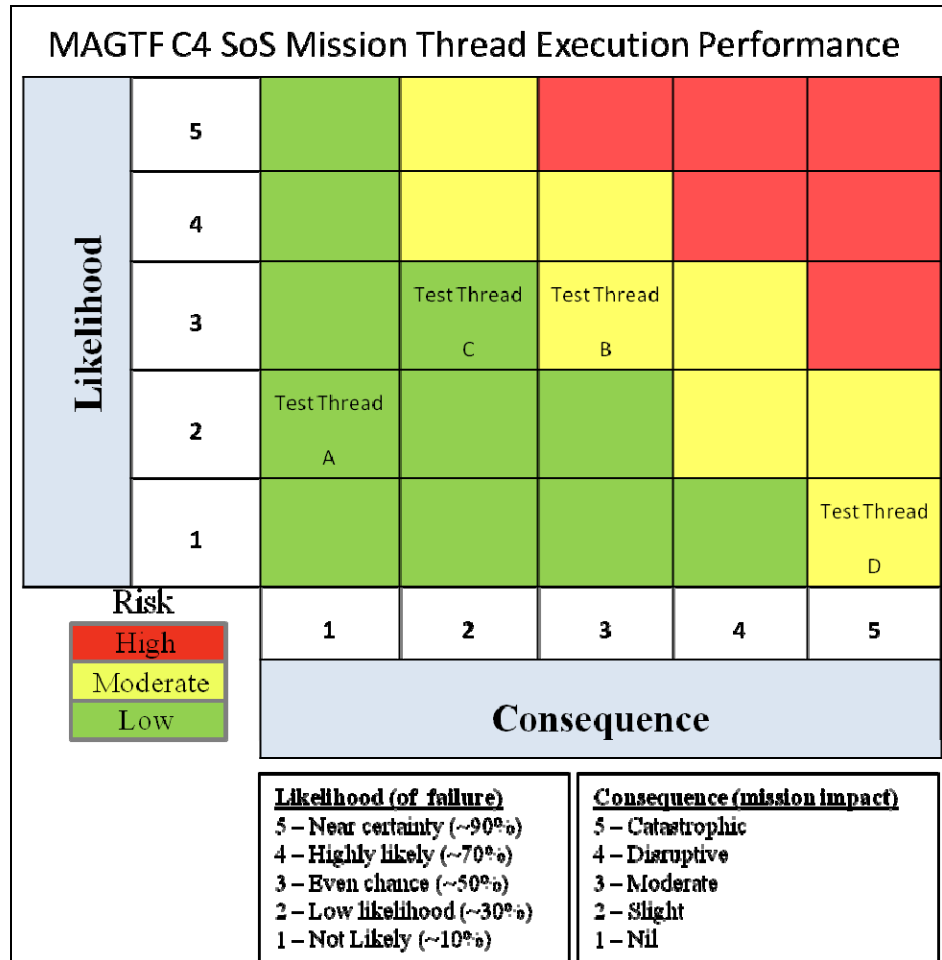
Figure 8.　　MC3 Risk-based SoS Performance Assessment Reporting.
MCTSSA's MC3 SoS Assessment risk chart depicts risk associated with executing a
given test thread within a defined SoS architecture.

Without defined performance criteria associated with execution of the test thread,
the interpretation of the data to determine a risk measure was subjective and served only
as a characterization of risk associated with execution of the test thread. Performance
data obtained from the individual systems during execution of the test thread was used to
develop a measure of risk associated with the success of executing a test thread in the
SoS. The overall risk associated with executing Test Thread D (Figure 8) in the C4 SoS,
for example, is moderate with a low likelihood of failure, but catastrophic consequence to
the mission when it fails. Through this methodology an overall assessment of the

27

performance of the SoS could be obtained by taking an average or weighted average of the total test thread risk scores to provide an overall C4 SoS risk score for use as the SoS performance metric.

The intent was that this method would provide a level of abstraction that would be more acceptable to the key stakeholders (Program Offices with ownership of individual programs within the SoS), than a typical pass/fail grading criteria normally associated with formal test activities. While this reporting methodology does serve that purpose and does provide a means to characterize the overall SoS performance in terms of mission task execution, other key aspects of the C4 SoS; net-centric C4 SoS effectiveness and suitability attributes like reliability and timeliness measures used to obtain the risk measure for thread execution in the SoS are obscured.

4.   DoD and Joint Approaches to the Challenges

In the 2008 *Systems Engineering Guide for Systems of Systems*, a more operational user-centric approach to addressing the challenge of SoS is recommended:

> Because acknowledged SoS typically comprise existing (often fielded) systems (e.g., AOC, SIAP, MILSATCOM), data from operations is an important source of understanding the state of the SoS. Because the SoS will likely evolve based on incremental changes in individual systems, it is important to have a set of user-oriented metrics that can be applied in different settings over time. The SoS systems engineer uses data from these settings to analyze SoS performance and behavior; hence, the metrics should include measures that use data from operations. These SoS metrics should also be traceable to the capability objectives established for the SoS, and there may even be a need to rank the metrics by importance. These metrics should not change as the capability of the SoS matures unless the capability objectives themselves change. They must remain applicable as the SoS matures to assess whether the changes made are actually translating into better user support. When captured in an operational environment, metrics allow an independent view to assess SoS performance from the user's perspectives, and allow assessment of the impacts of external factors on capability objectives. These operational user-based performance assessments do not substitute for the technical reviews and assessments performed during the process of upgrading the systems in the SoS. (OSD, 2008, p. 44)

28

This guidance implies greater reliance on users to define performance metrics of the SoS during employment in an operational context. As an approach recommended for an Acknowledged SoS, this would be very applicable to a MAGTF C4 SoS, however the measured attributes of the SoS (which are not defined by this guidance) would need to be carefully selected to accommodate the inherent variations in MAGTF C4 SoS implementation. User provided data on network loading and battle-rhythm induced variation in network-data traffic patterns would be directly applicable to MAGTF C4 SoS testing: providing operationally realistic base-line data that can be used to stress the SoS during assessment.

When JTEM reached the end of its three-year charter in 2009, the effort to continue work towards SoS test and evaluation continued at the Joint level through a DOT&E Special Project: Joint Test and Evaluation Methodology – Transition (JTEM-T). Chartered through 2011, JTEM-T continues to refine the JTEM CTM concept with specific focus on decomposing "…Joint Mission Threads (JMT) into mission- and tasked-based testable measures" (Walters, 2010, p. 3). The JTEM-T effort established a metrics working group with the goal of developing by the end of Fiscal Year 2010:

- A repeatable process for decomposing JMTs into testable measures

- Actual testable measures for selected JMTs

- A report to DOT&E on recommended changes to the Joint Capabilities Integration and Development Systems to facilitate testing in a joint environment

- A report through DOT&E to the OUSD/AT&L TRMC recommending the tools and instrumentation needed to support the use of JMT testable measures. (Walters, 2010, p. 4)

The significance of this is the promise of a database of mission-based test threads and associated metrics for warfighting capability-based SoS assessment at the Joint and Component level. These test threads may also be adapted for MAGTF C4 SoS assessment, providing stimulus and another measure of performance during C4 SoS assessment.

At the Joint level, progress has been demonstrated towards maturation of the infrastructure (through JMETC), methodology (through JTEM) and initial mission- and tasked-based testable measures (through JTEM-T) necessary for Joint SoS test and evaluation. While these products may be appropriate for adaptation by the Marine Corps for a MAGTF SoS assessment, they do not provide a complete solution for assessing the MAGTF C4 SoS. At the JTF or MAGTF level, the mission task itself serves as focus of assessment as a measure of the overall warfighting capability (how well, how quickly, how efficiently the SoS prosecutes the mission). The MAGTF C4 SoS contributes towards the overall warfighting capability by providing a C2 capability and, from that perspective, metrics associated with assessing the SoS in terms of providing the C2 capability (in line with the MAGTF C2 SoS assessment approach) would seem the most appropriate. However there is also value in assessing the performance in terms of mission thread execution and net-centric C4 SoS effectiveness and suitability (in line with the MC3 effort) (Figure 9).
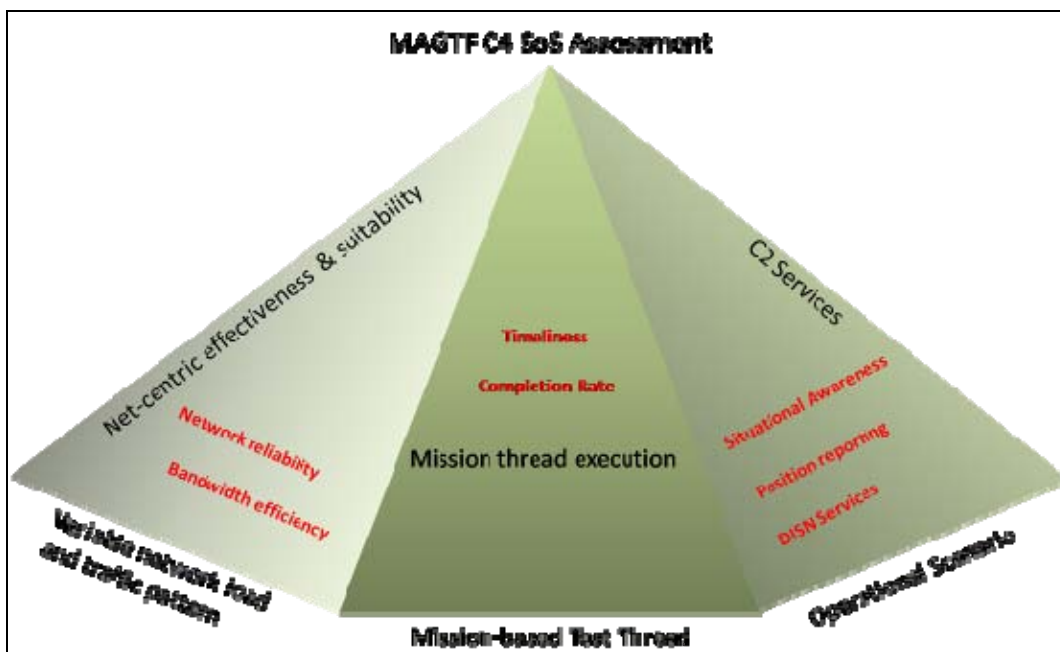
Figure 9   MAGTF C4 SoS Assessment Metrics.
A complete MAGTF C4 SoS assessment should include metrics related to net-centric effectiveness and suitability, mission thread execution and C2 services.

Documenting and reporting the results of the SoS performance assessment in a comprehensive, consistent and useful manner continues to be a challenge. This challenge is due in part the fluidity of the SoS assessment approach (defining test threads and metrics) but is also due to the complex nature and broad scope associated with characterizing the behavior of a large scale SoS. Characterizing a SoS in terms of risk that may be decreased or increased through a change in SoS baseline configuration may have some value. Other approaches, such as characterizing the SoS in terms of interoperability, may also have value and are the subject of a number of independent efforts in DoD and the commercial sector.

F.   SUMMARY

As the definition of a SoS within a DoD operational context has evolved and matured, so have the engineering approaches to developing and assessing a SoS. At the Joint SoS level, the warfighting capability serves as the focus of assessment, enabled by the JMETC distributed SoS testing infrastructure, InterTEC test tool suite, JTEM process and procedures and JTEM-T Joint Mission Threads (JMTs). This Joint SoS assessment methodology can be leveraged for Component SoS assessment (MAGTF as the Marine Corps Component) by adapting appropriate mission threads to the component warfighting capabilities.

For the MAGTF C4 SoS, the C2 capability that enables the C2 warfighting function provides the focus for SoS assessment. Executing mission-based test threads within a MAGTF C4 SoS that is stressed through an operationally realistic variable network load and data traffic patterns, provides an appropriate foundation for an assessment. Determining the specific attributes of the SoS to measure continues to be an evolving process. For the Marine Corps' MAGTF C4 SoS, a blend of a number of approaches may provide a more holistic assessment of the SoS. With an assessment of mission thread execution (timeliness, completion percentage), C2 services (situational awareness, position reporting, collaboration, and other Defense Information Systems

31

Network (DISN) services) and net-centric C4 SoS effectiveness and suitability (bandwidth efficiency, network reliability), a more comprehensive measure of SoS performance can be obtained.

As the techniques, processes and procedures for executing SoS assessments mature, there is an increasing need to convey the assessment results in a context that provides a more useful and meaningful characterization of the SoS performance. In the next sections a select sampling of commercial tools and techniques will be examined that may aid in this effort.

III. CURRENT ASSESSMENT TOOLS WITH POTENTIAL APPLICABILITY TO MARINE CORPS C4 SOS PERFORMANCE ASSESSMENT

A. INTRODUCTION

The Marine Corps C4 SoS performance assessment effort contributes to ensuring that the fielded C4 SoS provides an end-to-end integrated C2 solution for the Marine Corps Operating Forces. Optimally this assessment would address all aspects of the SoS: people (C4 operators and maintainers), processes (guided by doctrine and written procedures) and technology (communications systems, networking systems and C2 applications). However, in that respect, even the assessment of the smallest MAGTF (MEU), would require considerable resources to include as many as 2500 operators. In practice then, the SoS assessment out of practical necessity must be conducted through a modeled abstraction of a MAGTF C4 SoS. Typically, the representative MAGTF C4 SoS designed for the assessment is a sampling of equipment and software applications sufficient for executing select mission-based test threads and providing sufficient interactions to invoke the SoS behavior necessary to provide a basis for performance measurement. Furthermore, the assessment focuses primarily on the technology aspects of the SoS (the material solution for C2) to minimize the need for end-user operators and maintainers and lessen impact to the Marine Corps Operating Forces. Other key aspects of the SoS (both people and processes) serve as acknowledged constraints to the conduct of the SoS assessment and require assumptions regarding operator training level and fidelity of the processes associated with the SoS. While these aspects are integral to the overall SoS performance, a more narrow focus on the technical aspects of the MAGTF C4 SoS provides a more granular evaluation of this aspect than typically afforded by a formal MCOTEA Operational Test and Evaluation capability-based test of effectiveness and suitability.

Even with this focused approach and corresponding reduction in scope and complexity, characterizing the performance of the SoS in terms of the criteria associated with the technology is a challenge in and of itself. MCTSSA's MC3 assessment effort

attempts to do this through a composite of various performance metrics to produce an overall risk-based assessment characterization of the SoS. This approach, while relating SoS performance to execution of a mission-based test thread and providing some level of traceability of the thread execution to the contributions of individual systems within the SoS, has only been demonstrated in the Marine Corps MC3 effort with relatively small numbers of systems (5-10) in the SoS test framework. To assess a SoS during execution of more complex mission-based test threads or simultaneous execution of multiple test threads that involve significantly more systems as well as invoke more complex network behaviors, the need for assessment tools becomes evident. In addition to helping with management of greater quantities of data, assessment tools can help with standardizing the methodology for reporting, weighting and summing the SoS metric data for an overall SoS performance assessment. A sampling of some assessment tools that attempt to do just that is examined below.

B.   ASSESSMENT TOOLS

A theme common to a number of the tools proposed for SoS assessment is the idea of using interoperability as an overall SoS performance measure. However, much like the definition of SoS, interoperability must also be defined in a relevant context. The *DoD Dictionary of Military and Associated Terms* defines interoperability as:

1. The ability to operate in synergy in the execution of assigned tasks.

2. The condition achieved among communications-electronics systems or items of communications-electronics equipment when information or services can be exchanged directly and satisfactorily between them and/or their users. (Joint Chiefs of Staff, 2009)

The first definition aligns nicely with the basic definition and concept of a SoS, the second with the focus on the technology aspects of a SoS during an assessment event. Both definitions would then seem to imply that interoperability could serve as a focus for assessing overall SoS performance.

In 2004, the DoD contracted Carnegie Mellon Software Engineering Institute to examine the concept of interoperability and define a SoS interoperability (SOSI) model.

The model described in their final report incorporates aspects of technical interoperability, operational interoperability and programmatic interoperability. The SOSI model draws on technical and operational interoperability concepts introduced by the Levels of Information System Interoperability (LISI) model, NATO C3 Technical Architecture (NC3TA) Reference Model for Interoperability, the Organizational Interoperability Maturity Model (OIM) and Levels of Conceptual Interoperability Model (LCIM). The idea of programmatic interoperability is introduced as another dimension of interoperability by the SOSI model to recognize the influence that acquisition activities have on achieving the aspects of interoperability (Morris, Levine, Meyers, Place & Palakosh, 2004). Different levels of sophistication of SoS interoperability are central to all the interoperability models and closely parallel the concept of different types of SoS (Virtual, Collaborative, Acknowledged and Directed) defined in *Systems Engineering Guide for Systems of Systems* (OSD, 2008). The technical and operational aspects of interoperability also closely parallel aspects of how we view a SoS from an assessment perspective. This further strengthen the argument for using a measure of interoperability as a means of assessing overall SoS performance.

1. i-Score

Developed by Major Thomas Ford, Dr. John Colombi, Dr Scott Graham and Dr David Jacques from the Air Force Institute of Technology (AFIT), the Interoperability Score (i-Score) model is intended to offer a more quantitative measure of assessing the interoperability of a SoS than the qualitative measure (levels of interoperability sophistication) provided by models like LISI, OIM and SOSI (Ford, Colombi, Graham & Jacques, 2007). The model asserts a number of strengths to include:

1. It is easily computed,

2. It is based upon an operational thread,

3. It makes use of existing architecture data,

4. It can be used for scenarios where one or more type of interoperability is represented (i.e., information and organizational interoperability)

5. It defines the optimum interoperability for a given operational thread allowing a decision maker to understand what the limits of his/her interoperability improvements are and what can realistically be done to improve interoperability for an operational interest and

6. It provides a means of drilling down into a process to discover where interoperability problems lie. (p. 2)

The model presents a mathematical means for measuring the interoperability of a SoS obtained by analyzing the SoS components that contribute to the execution of a mission test thread. A mathematical score (i-Score measure) is calculated based on the values attributed to the interactions between components (value of -1,0 or 1 assigned depending on degree of data translation needed between components) and the number of times the component is used during execution of the mission thread. The i-Score measure is obtained through a six step methodology summarized by Ford, Colombi, Graham and Jacques (2006) as follows:

Step 1 – Diagram the operational thread (e.g., time-critical-targeting) using an IDEF0, BPML, or UML activity diagram and define the ordered set T of systems supporting each activity in the thread.

Step 2 – Create an interoperability matrix $M = \left[c_{ij} s_{ij} \right]_{nxn}$ where n is the number of systems supporting the thread, $C = \left[c_{ij} \right]_{nxn}$ is a multiplicity matrix which describes the number of times a system is used in the thread, and $S = \left[s_{ij} \right]_{nxn}$ is a spin matrix where s_{ij}, $\varepsilon\{-1,0,1\}$, is a variable indicating no human or machine translation needed for a system pair (+1), machine translation required (0), or human translation required (-1). M can be augmented by multiplying additional matrices (layers) such as normalized bandwidth, probability of connection between system pairs, mission capable rate for systems, normalized cost, system reliability, etc.

Step 3 – Calculate the *i-Score* $I = \sum_{i=1}^{n} \sum_{j=1}^{n} m_{ij}$.

Step 4 – Calculate the optimum *i-Score* $I_{opt} = \sum_{i=1}^{n} \sum_{j=1}^{n} m_{ij} \Big|_{m_{opt}}$ where

36

$$M_{opt} = \left[c_{ij} s_{ij} \mid_{s_{ij} = \max\{s_{ij}\}} \right]$$ is the maximally upgraded interoperability matrix (i.e., upgrade all spins that can be upgraded in light of physical, fiscal and operational constraints).

Step 5 – Calculate the Interoperability Gap $I_{gap} = I_{opt} - I$.

Step 6 – Perform interoperability analysis to 1) determine ways of closing the interoperability gap through spin upgrades or using common systems, 2) determine average interoperability spin, 3) compare operational threads through a normalized i-Score, or 4) visualize the interoperability of a thread by graphing it on an Interoperability Terrain graph. (pp. 15–16)

During a MCTSSA MC3 SoS assessment in 2008, in addition to the risk-based reporting methodology used to quantify the performance of the C4 SoS, a demonstration of the i-Score methodology was conducted using an Immediate Close Air Support (ICAS) mission-based test thread as the basis for the demonstration. The ICAS test thread (Figure 10) was simplified for this demonstration to ensure all activities during the execution of the mission thread were conducted in a serial manner since the i-Score methodology did not easily accommodate parallel processes (Sjoberg, 2008).
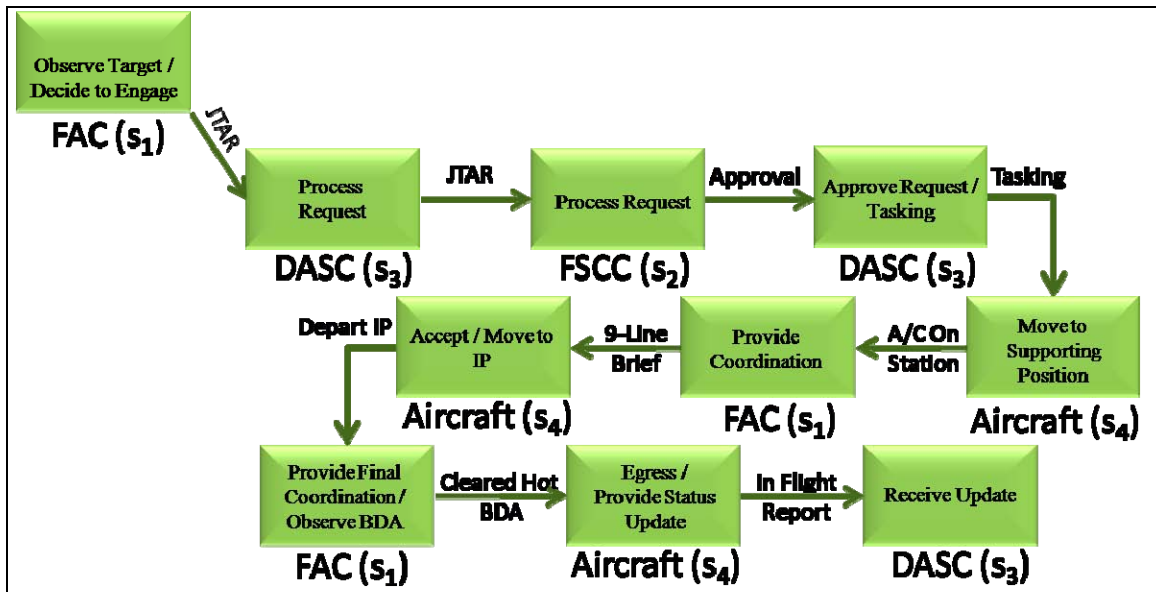
Figure 10.   MC3 08 Modified ICAS Test Thread.
Modified Immediate Close Air Support (ICAS) mission-based test thread used to demonstrate i-Score methodology during MCTSSA MC3 C4 SoS assessment in 2008 (After: Sjoberg, 2008).

The systems supporting the thread activity were identified as the Forward Air Controller (FAC), denoted as System 1 (s_1); the Fire Support Coordination Center (FSCC), denoted as System 2 (s_2); the Direct Air Support Center, denoted as System 3 (s_3) and the Aircraft (AC), denoted as System 4 (s_4). With the test thread defined, the six step i-Score methodology was applied as follows:

Step 1. From the mission thread in Figure 10, the ordered set T of systems supporting the ICAS mission thread was determined as reflected in Equation 3.1:

$$T=\{s_1,s_3,s_2,s_3,s_4,s_1,s_4,s_1,s_4,s_3\} \quad . \tag{3.1}$$

Step 2. The interoperability matrix (4x4 matrix: n=4 since we have 4 systems supporting the thread) is determined by Equation 3.2 (Ford et al., 2006):

$$M = \left[c_{ij} s_{ij} \right]_{nxn} , \tag{3.2}$$

where,

C = Multiplicity Matrix,

S = Spin Matrix.

The multiplicity matrix is determined by taking the elements of T two at a time in a forward direction (direction of mission thread execution) to determine set A (Ford et al., 2006). The intent is that this methodology accommodates both direct interaction as data is interchanged between components and indirect interaction that accommodates the upstream influences as the data progresses through the mission thread. For the ICAS thread then we determine set A in Equation 3.3 as follows:

$A = \{(s_1,s_3), (s_1,s_2), (s_1,s_3), (s_1,s_4), (s_1,s_1), (s_1,s_4), (s_1,s_1), (s_1,s_4), (s_1,s_3),$

$(s_3,s_2), (s_3,s_3), (s_3,s_4), (s_3,s_1), (s_3,s_4), (s_3,s_1), (s_3,s_4), (s_3,s_3), (s_2,s_3),$

$(s_2,s_4), (s_2,s_1), (s_2,s_4), (s_2,s_1), (s_2,s_4), (s_2,s_3), (s_3,s_4), (s_3,s_1), (s_3,s_4),$

$(s_3,s_1), (s_3,s_4), (s_3,s_3), (s_4,s_1), (s_4,s_4), (s_4,s_1), (s_4,s_4), (s_4,s_3), (s_1,s_4),$

$(s_1,s_1), (s_1,s_4), (s_1,s_3), (s_4,s_1), (s_4,s_4), (s_4,s_3), (s_1,s_4), (s_1,s_3), (s_4,s_3)\}. \tag{3.3}$

The pair (s_1,s_1) appears in set *A* three times which defines $C_{1,1}$, and pair (s_1,s_2) appears in this set one time which defines $C_{1,2}$ and so on to result in the multiplicity matrix defined in Equation 3.4 (Ford et al., 2006):

$$C = \left[c_{ij}\right]_{nxn} = \begin{bmatrix} 3 & 1 & 5 & 6 \\ 2 & 0 & 2 & 3 \\ 4 & 1 & 3 & 6 \\ 3 & 0 & 3 & 3 \end{bmatrix}. \qquad (3.4)$$

For the spin matrix, a pair-wise comparison and analysis was completed for each system and relative interoperability with each other. The results of the analysis are reflected in Table 2:

Spin element	Spin	Max Spin	Rationale
s_{ii}	1	1	All systems have perfect interoperability with themselves, which is to say $s_{ij} = s_{ji}$.
s_{12}	0	1	The FAC's Target Location, Designation and Hand-Off System (TLDHS) does not communicate directly to the FSCC's Advanced Field Artillery Tactical Data System (AFATDS) or Intelligence Operations Workstation (IOW). Instead the FAC sends information directly to the DASC which forwards the information on to the FSCC. It is possible for the TLDHS to communicate directly with the FSCC so this spin is upgradeable to 1.
s_{13}	1	1	The FAC's TLDHS enables direct data exchange with the DASC.
s_{14}	1	1	The FAC's TLDHS enables direct data exchange with the aircraft.
s_{21}	0	1	The FSCC must pass information through the DASC to communicate to the FAC. It is physically possible to establish digital communication from the FSCC to the FAC directly so this spin is upgradeable to 1.
s_{23}	1	1	The FSCC and DASC can conduct direct data exchange using IOWs and AFATDS.
s_{24}	0	0	The FSCC cannot conduct direct data exchange with the aircraft and must do so through the DASC. This is not upgradeable since there is no requirement for the FSCC to interoperate directly with the aircraft.
s_{31}	1	1	The DASC communicates directly with the FAC using IOW or AFATDS and TLDHS.
s_{32}	1	1	The FSCC and DASC can interoperate using IOW and AFATDS.
s_{34}	-1	1	The DASC only exchanges data with the aircraft using a human translator over voice channels. This spin is upgradeable since digital communication is possible between these two entities.
s_{41}	1	1	The aircraft can interoperate directly with the FAC's TLDHS.
s_{42}	0	0	The FSCC and aircraft cannot directly exchange data and must do so through the DASC. This is not upgradeable since there is no requirement for the FSCC to interoperate directly with the aircraft.
s_{43}	-1	1	The aircraft only provides data to the DASC using a human translator over voice channels. This spin is upgradeable since digital communication is possible between these two entities.

Table 2.   Spin Analysis.
Analysis of the modified ICAS test thread results in assignment of Spin values for each direct interaction between components in the test thread (From: Sjoberg, 2008).

From the spin analysis a spin matrix (S) and optimal spin matrix (S_{opt}) are determine in Equations 3.5 and 3.6 (Ford et al., 2006):

$$S = \left\lfloor s_{ij} \right\rfloor_{nxn} = \begin{bmatrix} 1 & 0 & 1 & 1 \\ 0 & 1 & 1 & 0 \\ 1 & 1 & 1 & -1 \\ 1 & 0 & -1 & 1 \end{bmatrix}, \tag{3.5}$$

$$S_{opt} = \left\lfloor s_{ij} \right\rfloor_{nxn} = \begin{bmatrix} 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 0 \\ 1 & 1 & 1 & 1 \\ 1 & 0 & 1 & 1 \end{bmatrix}. \tag{3.6}$$

Now with the multiplicity matrix (C), spin matrix (S) and optimal spin matrix (S_{opt}) defined, the interoperability matrix (M) and optimal interoperability matrix (M_{opt}) can be determined as reflected in Equations 3.7 and 3.8:

$$C = \begin{bmatrix} 3 & 1 & 5 & 6 \\ 2 & 0 & 2 & 3 \\ 4 & 1 & 3 & 6 \\ 3 & 0 & 3 & 3 \end{bmatrix}, S = \begin{bmatrix} 1 & 0 & 1 & 1 \\ 0 & 1 & 1 & 0 \\ 1 & 1 & 1 & -1 \\ 1 & 0 & -1 & 1 \end{bmatrix} \Longrightarrow M = \begin{bmatrix} 3 & 0 & 5 & 6 \\ 0 & 0 & 2 & 0 \\ 4 & 1 & 3 & -6 \\ 3 & 0 & -3 & 3 \end{bmatrix}, \tag{3.7}$$

$$C = \begin{bmatrix} 3 & 1 & 5 & 6 \\ 2 & 0 & 2 & 3 \\ 4 & 1 & 3 & 6 \\ 3 & 0 & 3 & 3 \end{bmatrix}, S_{opt} = \begin{bmatrix} 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 0 \\ 1 & 1 & 1 & 1 \\ 1 & 0 & 1 & 1 \end{bmatrix} \Longrightarrow M_{opt} = \begin{bmatrix} 3 & 1 & 5 & 6 \\ 2 & 0 & 2 & 0 \\ 4 & 1 & 3 & 6 \\ 3 & 0 & 3 & 3 \end{bmatrix}. \tag{3.8}$$

Step 3. From M, an *i-Score* (I) as determined from Equation 3.9 (Ford et al., 2006):

$$I = \sum_{i=1}^{n} \sum_{j=1}^{n} m_{ij} \quad , \tag{3.9}$$

is then calculated for the ICAS test thread as I=21.

Step 4. From M_{opt} , the optimum i-Score (I_{opt}) as determined from Equation 3.10 (Ford et al., 2006):

$$I_{opt} = \sum_{i=1}^{n} \sum_{j=1}^{n} m_{ij} \Big|_{m_{opt}} \quad , \tag{3.10}$$

is then calculated as $I_{opt} = 42$.

Step 5. The Interoperability Gap (I_{gap}) as determined from Equation 3.11 (Ford et al., 2006) :

$$I_{gap} = I_{opt} - I \tag{3.11}$$

is then calculated with I_{gap}= 21.

Step 6. From the initial analysis, two interoperability factors were identified that could close the interoperability gap: the inability of the DASC to digitally communicate with the aircraft and the inability of the FSCC and FAC to directly exchange date. Addressing the first factor would close the I_{gap} score by 18 points. Addressing the second factor was determined to have little operational relevancy (Sjoberg, 2008).

To provide a higher level of fidelity to the model, an improved version was offered in 2008. The improved i-Score methodology replaces the discrete values of the spin matrix with continuous values that describe each system's relative interoperability in what is then termed a resemblance matrix. The modification to the model is described by Ford, Colombi, Graham and Jacques (2008) as follows:

> The nature of each system is described as a set of system character states, which set is called a system instantiation. The resemblance of each instantiation pair is measured using a distance metric, and the resulting set of resemblance coefficients is given as a resemblance matrix. The *i-Score* interoperability measurement method is then upgraded by replacing the original spin matrix with the resemblance matrix. Because the coefficients in the resemblance matrix represent exact measures of similarity between systems, based upon system characters pertinent to interoperability, the

measure of interoperability obtained enjoys more fidelity and accuracy than that possible with the original spin-based method. (p. 2)

As applied to the MAGTF C4 SoS assessment effort, i-Score provides a methodology for determining and quantifying the relative interoperability of a mission-based test thread under the supposition that the optimal interoperability of any SoS is obtained with maximum direct digital communications between components (no human or machine translation required). The maturity of the interface between systems or components in the SoS serves as the basis for the SoS assessment then, with direct digital communications representing the highest maturity and human translation representing the lowest maturity. From an operational thread perspective, there are often many ways to execute a mission or task with varying degrees of human interaction (multiple combinations of systems and procedures available to accomplish the same mission). Subsequently, a test organization must select from a number of possible test threads that meet the mission requirement. In this respect, the i-Score methodology can assist with defining the test threads that promise optimal interoperability (threads with least human translation required) and help narrow the selection for inclusion in a test event. Additionally, during execution of the test thread for an assessment event, the relative impact of a deviation during thread execution (e.g., human translation required due to component translation failure) could be immediately quantified through a recalculation of the i-Score. Further analysis of the improved i-Score methodology may yield further application with added value to a C4 SoS assessment effort.

2.   Interoperability Quotient

The Interoperability Quotient (IQ) process was developed by Northrop Grumman Corporation to address complex SoS testing related to the Navy's CVN-21 next generation Aircraft Carrier program. IQ was presented to the Joint test community during the June 2007 JMETC User Group Conference in Dulles VA, as a more objective approach to performance assessment during Joint SoS test events. Much like i-Score, this methodology addresses the lack of a quantitative measure for assessing C4 SoS interoperability: noting that interoperability compliance with measures of performance such as NR-KPP lack objective metrics (Lawver, 2007).

The test process looks at interoperability from two perspectives: first, from the perspective of data transfers between individual components of the SoS (external tests) and second, from the perspective of data processes within the individual components of the SoS (internal tests). This approach is referred to by Northrop Grumman as the "interoperability test stack" or "IQ Stack" to draw parallels to modular functional data models like the Open System Interconnection (OSI) 7-layer stack (Lawver, 2007).

As depicted in Figure 11, the external tests look at data interaction between the systems within the SoS in terms of vulnerability, Web standards compliance, edge condition testing, Service Oriented Architecture (SOA) technologies, data transmission bandwidth, corrupted data and security. The internal tests look at attributes of the individual systems within the SoS in terms of Human Computer Interface (HCI) and Symbology, business rules for data fusion, Information Assurance (IA) and semantic interoperability (Lawver, 2007).
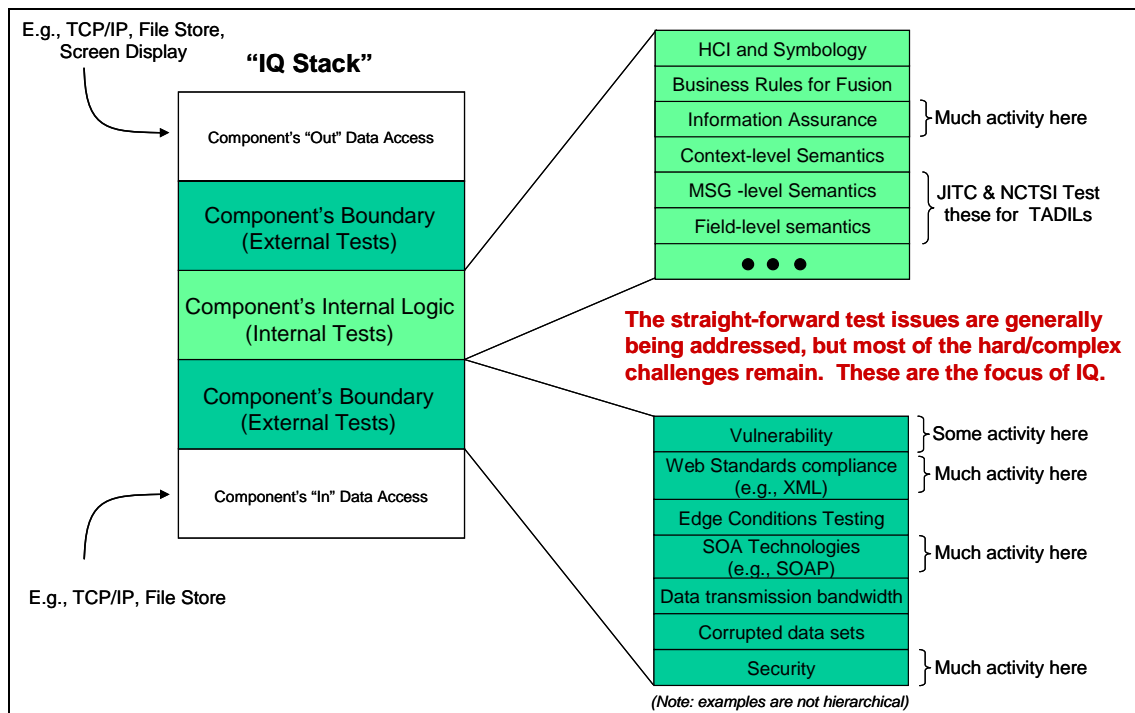
Figure 11.   Northrop Grumman "IQ Stack".
The Northrop Grumman IQ Stack depicts aspects of both internal and external data interactions between components in a SoS (From: Lawver, 2007).

44

The IQ process is conducted within the context of an operational mission test thread that provides the basis for evaluation of the components (command centers, platforms, individual systems or applications) in the SoS. As the thread is executed, internal and external test artifacts are collected for the components and manually scored based on an established scoring criteria (numerical score associated with each possible outcome). As the numeric scores are determined, a color code (green-pass, yellow-caution, and red-fail) is also assigned. Both internal and external test scores are rolled up for an overall score and then those scores are rolled up to provide an overall component IQ score (maximum 200-point scale) and overall color code for the component (Lawver, 2007). This roll up methodology as depicted in Figure 12, also allows for specific weighting of individual tests to accommodate specific design capabilities to help normalize the score to the 200-point scale (Lawver, 2007). Of note is that the validity of the roll-up methodology is dependent on the scoring methodology selected for the internal and external tests. If scoring is not based on a ratio scale, the summation and any statistical inferences will not be valid.
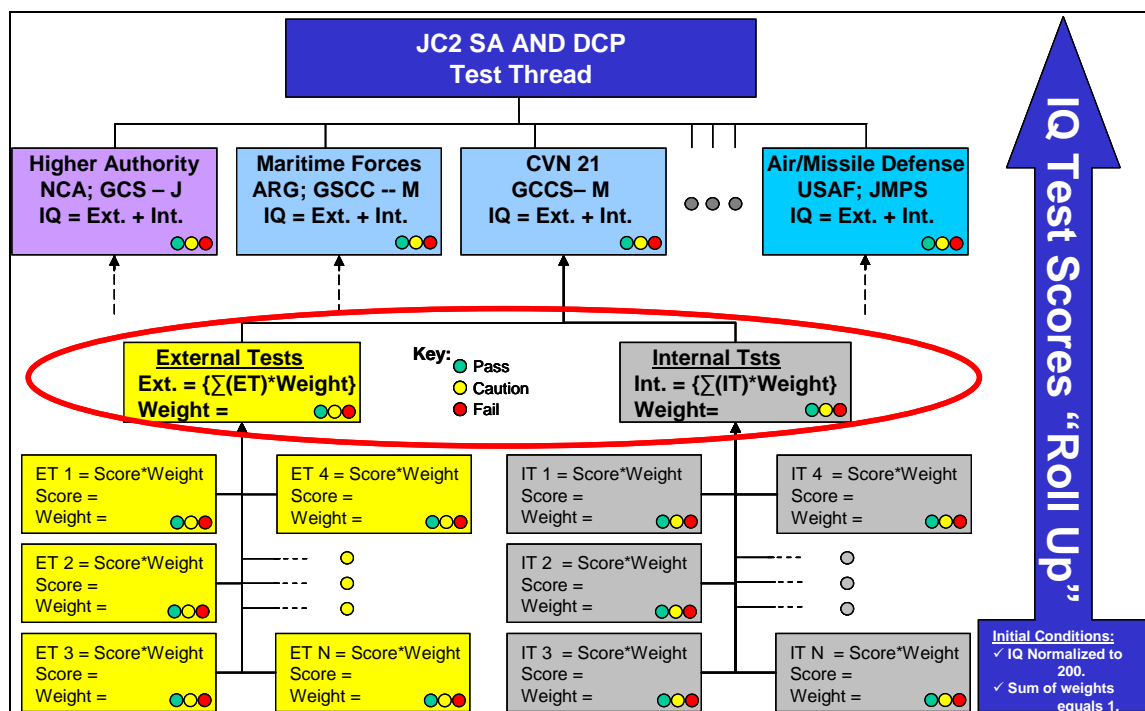
Figure 12.   IQ Computation Roll Up Methodology.
IQ rollup methodology is depicted for the GCSS-M component in the CVN-21 SoS
(From: Lawver, 2007).

To help better visualize and report the results of an interoperability assessment, Northrop Grumman also developed a companion Web portal tool called "Auto IQ" (Lawver, 2007) that provides a visual interpretation of the data and allows drill down to see how the individual scores are rolled up for the overall IQ component score. Depicted in Figure 13, the intent is to provide a means for analysts to drill down into the data for a better understanding of the overall component score and to provide the component program manager with insight into the individual test attributes that may serve as means to identify areas that can be addressed to improve component interoperability.

Figure 13.   "Auto IQ" Web Portal.
The Auto IQ Web Portal provides a convenient method to display SoS assessment results and a drill down capability to see how the components of a SoS contributed to the overall IQ score (From: Lawver, 2007).

From a MAGTF C4 SoS assessment perspective, the IQ methodology provides a similar approach to the MC3 risk-based reporting methodology with performance data obtained from the individual systems during execution of the test thread used to develop a measure of risk associated with the success of executing a test thread in the SoS. However, the IQ test model examines both internal and external interfaces through performance metrics that once defined, are intended to provide a quantifiable and repeatable metric that characterizes the overall interoperability of the SoS.

3. Dynamic Software Architecture Visualization and Evaluation (DynSAVE)

While not specifically offering a methodology that leads to an interoperability score, the Fraunhofer Center for Experimental Software Engineering Maryland (FC-MD) provides an approach for assessing the key interoperability aspects of digital information exchange. The FC-MD is a not for profit, applied research organization associated with University of Maryland that examines advanced software engineering techniques and conducts "applied research in software architecture, verification & validation, process improvement and measurement" (Ganesan, Lindvall, Bartholomew, Blau, McComas, & Cammarata, 2008, p. 4). To address the issues with performance of complex software SoS, the FC-MD developed an approach for assessing software SoS performance and identifying problems with communications between systems. The approach was derived from an initial effort in support of Johns Hopkins University Applied Physics Laboratory (JHU/APL) Space Department and the development of Mission Operations Center (MOC) system software used by NASA missions. The MOC system software used a shared architecture called the Common Ground System (CGS) and because of its age (10 years old), presented challenges when MOC software modification were required in support of new mission requirements (Stratton, Sibol, Lindvall, & Costa, 2006).

To address this challenge, FC-MD in a collaborative effort with the Fraunhofer Institute for Experimental Software Engineering (IESE) developed and applied the Software Architecture Visualization and Evaluation (SAVE) tool and process:

> This process comprised defining a planned architecture including architectural goals and design rationale, generating a high-level description of the actual architecture from the legacy software, identifying deviations between the planned and actual architecture, creating a new target architecture, and creating a roadmap to align on-going systems development and maintenance with new target architecture. (Stratton et al., 2006, p. 1)

The SAVE tool provides a means to automatically extract architectural views from the application's source code and checks the compliance of source code with the planned architecture (Ganesan et al., 2008) as depicted in Figure 14.
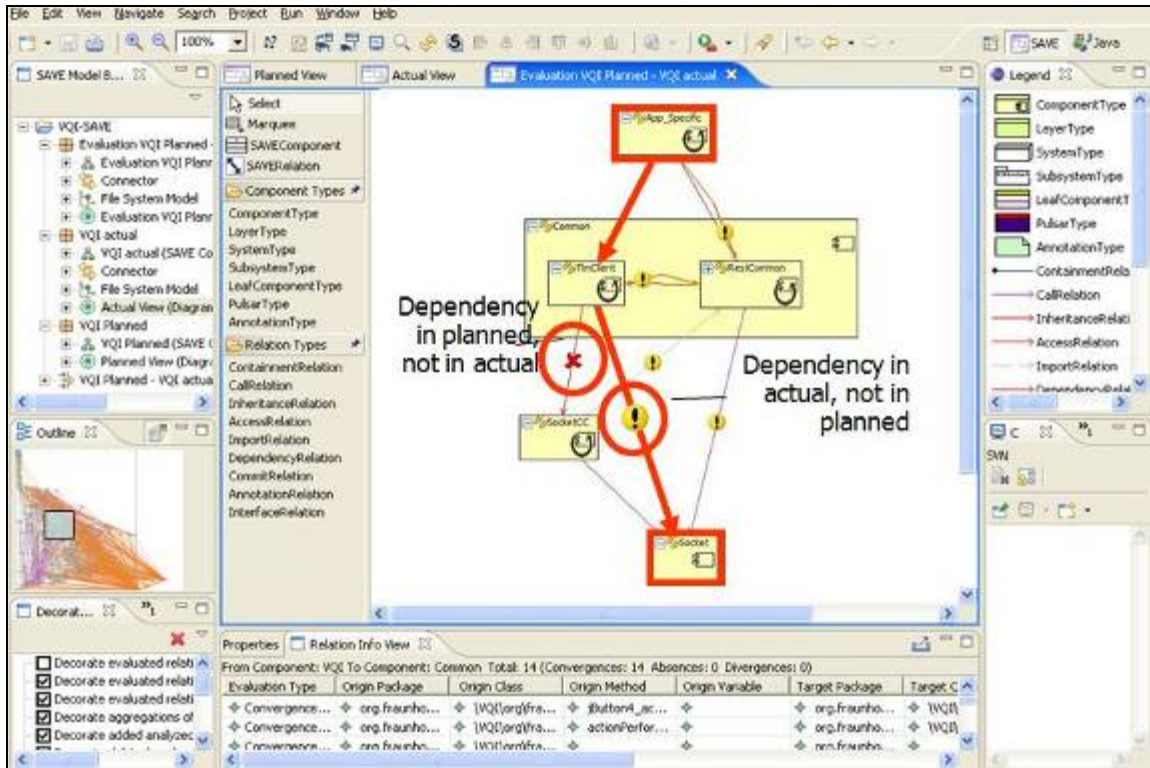
Figure 14.   SAVE Tool Analysis.
The SAVE tool, provides a means to automatically extract architectural views from the application's source code for comparison with the planned architect (From: Ganesan et al., 2008, p. 9).

Primarily applicable to single software applications, SAVE conducts static analysis of software systems written in a variety of languages (C/C++, Java, Delphi, Simulink, and others) to identify variances (violations of interaction between components) in planned versus implemented software architecture (Stratton et al., 2006).

In a follow-on effort, FC-MD extended the functionality of SAVE to provide an ability to conduct dynamic analysis of a software SoS. The new product called DynSAVE (Dynamic SAVE) provides both structural and behavioral architecture analysis of a SoS. Asserting that the reliability of inter-systems communication determines the success of the overall capability of a SoS, DynSAVE provides an approach for capturing, processing, and visually representing communications behavior of a SoS for analysis (Stratton, Sibol, Lindvall, Ackermann & Godfrey, 2009).

48

The challenge associated with inter-systems communications typically stem from individual systems implementation of communications protocols. While the protocols are typically defined in the system's Interface Control Document (ICD), a number of factors influence the implementation of protocols that can result in degraded SoS performance:

1. The systems are often developed independently from each other by different development teams at different locations.

2. The communication behavior of each individual system is not and cannot be fully tested in the environment it will eventually operate in, but rather by using components that simulate the communication of other systems.

3. The ICD that specifies the protocol is ambiguous as it omits details allowing developers to interpret the protocol differently.

4. The ICD consists of hundreds of pages of text written in natural language, making it difficult for developers to fully understand and implement. In the case of CFDP, most implementations only support the commonly used features of the protocol, so issues with integration of differing subset implementations emerge.

5. Many clients exist that implement the ICD protocol and it would be a significant effort to update them if the protocol was changed.

6. Violations of the protocol are not clearly visible but manifest themselves as some kind of misbehavior. (Stratton et al., 2009, p. 3)

Subtle difference in protocol implementation can result in anomalies in communications behavior that impact reliability and efficiency of the SoS. The DynSAVE methodology classifies the anomalies in terms of Sequence (defining the order of interaction between systems during message exchange), Parameters (control signals and data within a message that controls system behavior) and Timing (time constraints of message exchange between systems). The DynSAVE approach depicted in Figure 15 involves capturing raw data during communication exchanges, mapping the raw data to protocol, and then visualizing the communications behavior in a sequence diagram for interpretation and evaluation of the message exchange between systems within a SoS.

49
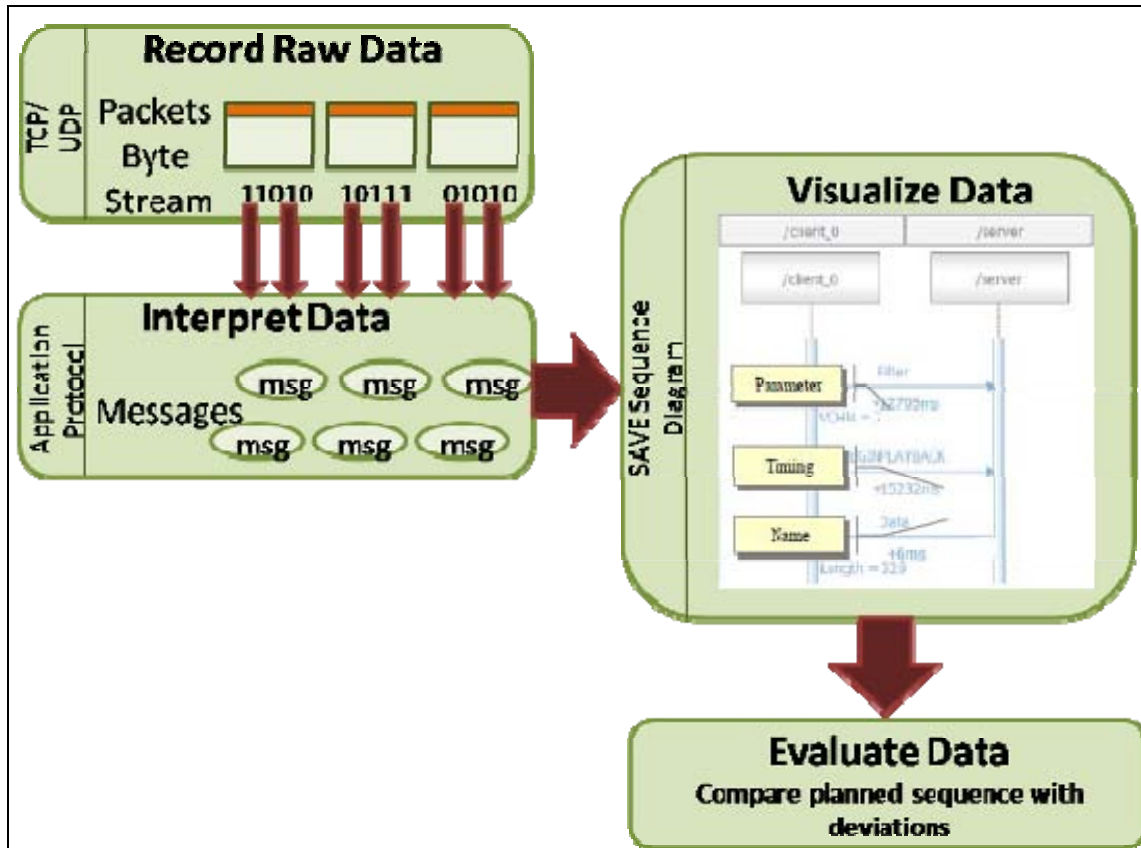
Figure 15.   DynSAVE Process.
The DynSAVE Process captures raw data for interpretation and visualization in a
sequence diagram (After: Stratton et al., 2009, p. 6).

While the MC3 MAGTF C4 SoS assessment approach has looked at capturing
emergent or unexpected behavior within the SoS during execution of a SoS performance
assessment in a qualitative manner, DynSAVE may provide a means for applying a more
quantitative measure to anomalous behavior. Although limited to IP-based protocols,
DynSAVE can provide greater insight into the origins of anomalous behaviors in a
complex SoS in terms of the sequence, parameters and timing attributes of digital
communications: offering a means of quantifying the anomalous behavior and related
measure of efficiency and reliability of a SoS through those attributes.

C.   SUMMARY

A key and certainly foundational aspect of the C4 SoS is the myriad of software systems that process the data necessary to provide the C2 capability. The interoperability assessment of both i-Score and IQ address this with a specific focus on interfaces and data exchange between components that are primarily software systems or software systems within a functional component of the SoS (e.g. AFATDS in the DASC component). As depicted in Table 3, the i-Score methodology examines the interface from a macroscopic level assigning a value to the relative maturity level of the digital interface between components. The IQ methodology goes a step further suggesting that both interface between components and internal processing within a component are necessary to derive an overall SoS interoperability metric. However examining the internal logic and boundaries of the components within a complex SoS is not trivial. To address this complexity, the FC-MD DynSAVE tool and process provides an approach for identifying and visualizing digital communications' anomalies to convey a better understanding of the information exchange attributes that influence both the efficiency and reliability aspects of a SoS.

Assessment Tool	Attributes and Applicability to MAGTF C4 SoS Assessment	Limitations
i-Score	- Quantitative approach for measuring SoS interoperability through metric associated with interfaces between components - May provide means for selecting test thread based on i-Score metric and relative interoperability - May provide a means to quantify deviation from intended thread execution during an assessment	- Accommodation of parallel processes in test thread - No direct correlation between interoperability score and SoS performance metrics
IQ	- Quantitative approach for measuring SoS interoperability through metric associated with interfaces between components and processing within a component. - May provide a methodology for more clearly defining SoS assessment metrics - May provide a means to better visualize how lower level metrics contribute to overall SoS assessment metric	- Interoperability scoring methodology relies heavily on subjective scoring and weighting of interoperability attributes - Summation methodology only valid if scoring is based on a ratio scale - No direct correlation between interoperability score and SoS performance metrics
DynSAVE	- Tool and process for identifying and visualizing anomalies associated with digital communications within a SoS - May provide a means to quantify SoS anomalies and aspects of efficiency and reliability	Applicable to software C4 SoS transactions only (does not accommodate non-digital transactions and components that may contribute to the efficiency and reliability of the SoS as a whole)

Table 3.   Assessment Tool Summary.
Attributes, application and limitations of three SoS assessment tools.

While the tools described in this section all offer unique methodologies for assessing SoS performance that may help to better quantify the performance of a MAGTF C4 SoS, they are also very similar in that they each examine information exchanges at the component level to derive an overall SoS performance assessment measure in terms of interoperability.   In the next section, multicriteria identification is examined as a means to accommodate not only the interoperability measure of a SoS but other attributes as well for a more holistic and complete assessment of the SoS.

THIS PAGE INTENTIONALLY LEFT BLANK

IV. IMPROVING THE SOS MODEL THROUGH MULTICRITERIA IDENTIFICATION

A.   INTRODUCTION

The JMETC Joint SoS testing approach and MCTSSA C4 SoS assessment approach share similar features. For both, execution of a mission-based test thread provides the stimulus for the components of the SoS and serves a basis for providing an indication of SoS suitability (ability to complete the test thread). For both, the mission-based test thread is executed in a SoS that is to varying degrees, an abstract model of the actual SoS employed by the end-user (LVC concept).   The use of Modeling and Simulation (M&S) is not only necessary from a practical standpoint, but also aligned with the guidance provided in the 2008 *Systems Engineering Guide for Systems of Systems*:

> Models, when implemented in an integrated analytical framework, can be an effective means of understanding the complex and emergent behavior of systems that interact with each other. They can provide an environment to help the SoS SE team to create a new capability from existing systems and consider integration issues that can have a direct effect on the operational user.

> Because it can be difficult or infeasible to completely test and evaluate capabilities of the SoS, M&S can be very effectively applied to support test and evaluation at different stages throughout the SoS SE process. In particular the SoS SE team should consider M&S of the SoS to understand the end-to-end performance of the overall SoS prior to implementation. In some cases it is advisable for the SoS SE team to adopt a model-based process. (OSD, 2008, p. 10)

In another level of abstraction beyond the physical models that are instantiated as the basis of SoS testing and assessment by JMETC and MCTSSA, the construction and use of mathematical models that describe the behavior of a SoS would also seem relevant.   A mathematical model would provide a means for assessing behavioral characteristics resulting from changes to key SoS attributes in pursuit of understanding how and where improvements to the actual SoS can be made. However, developing a mathematical model that represents the complex behavior of a SoS is a significant challenge. Furthermore, even with that challenge addressed, obtaining an understanding

of how adequate or how closely the model can predict actual behavior is necessary before that model can be extended and used for any decision analysis.

A set of mathematical equations that describe the operation or performance of a system is fundamental to optimization problems. The equation variables and constraints associated with the equations define the design space and serve as the basis of analysis in pursuit of optimizing performance criteria. Looking at this process in reverse to determine and improve a mathematical model from observed operation and performance of a system is the basis of the identification process. Multicriteria identification provides an approach for determining the adequacy of a mathematical model relative to the actual behavior of the system or SoS that the model represents. Once the mathematical model is determined adequate, it can then be used for improving physical models or prototypes. In discussion of establishing adequacy through various identification methods, Statnikov and Matusov (2002) offer this perspective:

> In the most common usage, the term "identification" means construction of the mathematical model of a system and determination of the parameters (design variables) of the model by using the information about the system response to known external disturbances. In a sense, identification problems are inverse with respect to optimization problems. (p. 88)

From a SoS perspective, the mathematical model would ideally represent performance at the SoS level with determination of the parameters of the model obtained during execution of a mission task (external disturbance). The feasibility of constructing a mathematical model to represent the MAGTF C4 SoS and conceptual use of multicriteria identification for establishing and improving the test environment as well as adapting elements of the multicriteria identification process as part of the SoS assessment process itself are examined below.

B.   MAGTF C4 SYSTEM OF SYSTEMS PROTOTYPE

The representative MAGTF C4 SoS that serves as the foundation of the assessment process consists of computers, databases and applications that receive, manipulate, send and display data over a communications and computer network

infrastructure for use by machines or humans during the prosecution of a mission thread. While often consisting of many of the same components found in the Marine Corps Operating Force's C4 SoS, the representative C4 SoS in the test environment is usually an abstraction of the actual environment.

The test environment is a physical model of the actual SoS and may also be considered a prototype that can serve as an environment for testing new C2 applications, modifying system configurations or modifying communications protocols or networking attributes that we hope will improve, or at least do no harm to the actual C4 SoS. As we modify the prototype, the hope is the resulting performance, interoperability measure or other attributes of the SoS will adequately reflect what we would expect in the actual SoS. A complementary mathematical model that describes the behavior of the SoS would provide a means to improve the physical model or prototype through the multicriteria identification process.

C. MAGTF C4 SYSTEM OF SYSTEMS MATHEMATICAL MODEL

Mathematical modeling of C2 communications and network architectures is pursued for a variety of uses. One of the most widely known modeling constructs used within the Department of Defense (DoD) is OPNET Modeler. This modeling construct focuses primarily on communications systems and provides a capability for communications systems planning and performance prediction. Wargaming simulations like JANUS(T) use mathematical models that serve as the foundation for determining predictive outcome during military operational scenarios. These models focus on performance of military units with inherent C2 capabilities that can infer C2 performance (Ingber, Fujio, & Wehner, 2001).

Developing a mathematical model that describes the behavior of the MAGTF C4 SoS hints at the very essence of the SoS assessment challenge: defining the key SoS performance criteria. The key performance criteria that serve as the basis of an assessment are central to the construction of a mathematical model that describes the SoS. The i-Score and IQ methodologies quantify the SoS by applying the principles of decomposition and aggregation of large-scale systems with an analysis and a scoring

construct that defines an interoperability measure as the key performance criteria. Measuring interoperability at the individual system level is an approach shared by i-Score, IQ and DynSAVE. Improving the interoperability between components through i-Score, IQ or DynSAVE analysis would imply improved efficiency (reduction in human or machine processing requirements within the SoS as the thread is executed) and improved effectiveness (reduction in processing implies potential for quicker execution of the thread with less potential for introduction of error during translation from one component to the next). These approaches each provide a means for defining and measuring attributes at the systems level for aggregation into a meaningful overall interoperability measure that should correlate to the overall efficiency and effectiveness of the SoS.

While IQ and DynSave provide a means of deriving a measure of interoperability through observed and quantitative assessment of a SoS, only the i-Score methodology provides an approach to describing a SoS in terms of a mathematical model. The i-Score approach to modeling a SoS in terms of interoperability is not unique. Other approaches have been proposed to include a model that describes the SoS in terms of interoperability and complexity presented in *A Model for Assessing the Performance of Interoperable, Complex Systems* by Thomas Huynh and John Osmundson (2006). However, the use of a mathematical representation of a SoS in terms of interoperability is limited unless we can somehow correlate the interoperability measure with measurable performance criteria of the SoS. To address this common challenge, prototype experimentation may provide a means to help determine the correlation between an interoperability measure and performance of the SoS and then help improve the model through parametric identification (improving or determining the appropriate numerical values of the equation coefficients).

1. Prototype Experimentation Data to Develop and Improve Model

In a broader perspective, we would like to characterize the C4 SoS in terms of overall C2 effectiveness (ability to efficiently and effectively provide a C2 capability) as the main criterion. The SoS should provide a C2 capability while consuming as few

resources as possible (measure of efficiency) while enabling the successful execution of a mission thread as quickly as possible (measure of effectiveness). The interoperability measure addresses this in part, but with focus solely on thread execution and interoperability between systems, other attributes of the C4 SoS that are necessary to provide indirect or background C2 activities may not be adequately accommodated. Activities such as position reporting, DISN services, and maintaining Situational Awareness (SA) may contribute directly to the execution of a mission thread, but are also critical background processes that enable decision making to ensure the appropriate mission is executed at the appropriate time for successful execution of a warfighting campaign. From that perspective, a mathematical model would need to accommodate those activities as variables within the model (demand for services varies with the operational tempo and battle-rhythm that is driven by the operational scenario and echelon). Those variables as well as the activities directly engaged with execution of the mission thread are consumers of bandwidth and the quality of service related to those activities is dependent on bandwidth availability. Availability of bandwidth is generally a fixed constraint within the SoS although allocation of bandwidth within the SoS to specific C2 services can be optimized to best meet operational needs. Ideally, although beyond the scope of this study, a mathematical interoperability model would be correlated with measurable attributes of C2 effectiveness (such as bandwidth efficiency, resource usage and time to execute mission tasks), while accommodating the variable background activities and fixed bandwidth constraint.

a. *Simulation and Stimulation Considerations*

To accommodate the C2 background activities in the model, some thought must be given to how they can be represented in the prototype. The operational scenario serves as a reference for the mission-based test thread and drives the demand for C2 services. However, the demand for C2 background activities is largely dependent on the battle rhythm and operational tempo during mission execution and not necessarily dependent on mission execution itself. Real-world operational data can provide a basis for determining the variations in C2 background activities (Position Location Information or track load and DISN services such as VTC, telephone, and collaboration services) that

can be replicated in the C4 SoS prototype thorough various simulation and stimulation applications. Executing the test thread in the prototype environment under various mixes and load of C2 background activities will induce more realistic behavior necessary for developing a higher fidelity mathematical model.

The use of virtualization technology may also offer a more efficient means to establish a large-scale C4 SoS model. MCTSSA experimented with using virtualization technology to replicate a MAGTF C4 SoS during the 2008 MC3 assessment effort. Virtualization technology provided a means to rapidly construct the C4 architecture to validate individual component configuration settings and test procedures to be used during the assessment. Once configuration settings and test procedures were validated, the C4 architecture was constructed with actual C4 components for the assessment. This resulted in considerable time savings (2–3 days) over previous MC3 events by allowing the test procedure validation effort to be conducted in parallel with other pre-assessment preparation efforts. Use of a virtualized environment to conduct the actual assessment was not considered due to the unknown differences in performance between the virtual and actual C4 SoS models (Marine Corps Tactical Systems Support Activity, 2009).

b. *Data Collection Considerations*

Performance data related to C2 effectiveness can be obtained from a measure of the time to execute the mission thread. Performance data related to C2 efficiency may require use of tools to measure bandwidth utilization as a measure of efficiency or new tools like DynSAVE that capture the behavior of complex SoS data transactions for more detailed efficiency analysis.

In an operational C4 SoS, network optimization and Quality of Service (QoS) management are performed through use of commercial software tools such as Solar Winds' Orion Network Performance Monitor associated with the Joint Network Management System (JNMS) program of record, Cisco's suite of network management products associated with the TDN program of record, and Referentia's LiveAction network management solution associated with an Office of Naval Research (ONR)

development effort. While these tools serve as an integral part of the SoS, they are not always included in the test/assessment prototype environment since they do not directly contribute to the execution of a mission thread. However, if C2 background activities are incorporated within the SoS prototype, these tools are necessary to ensure the network is configured to reflect realistic operational requirements with respect to QoS and network performance optimization. Further, while these tools are an element within the SoS, one of their key functions is to provide internal diagnostics relative to the SoS network performance and while considered intrusive from a test environment data collection perspective, may still provide critical insight into and measurement of performance efficiency from a resource utilization perspective.

2. Multicriteria Identification

The complexity of a MAGTF C4 SoS may prohibit development of an adequate mathematical model in terms of a single performance criteria. Bandwidth efficiency, resource usage and time to execute mission tasks are three criteria identified earlier, but there could be many other performance criteria that must be considered to adequately describe the SoS—that is to say, a mathematical model that reflects the correlation between the interoperability measure and bandwidth efficiency performance measure may differ from the mathematical model that reflects the correlation between the interoperability measure and time to execute a mission task. Yet, both may be needed to adequately describe the SoS. This would indicate that correlating interoperability with SoS performance may very well be a multicriteria problem. Developing and improving the mathematical relationship between interoperability and SoS performance then would involve a multicriteria identification process: observing performance of the prototype during mission-based thread execution and through experimentation develop and improve the mathematical relationship.

a. Use of Adequacy Criteria to Improve the Models

Adequacy criteria (or proximity criteria) represent the discrepancy between the physical prototype model and the mathematical model (Statnikov & Matusov, 2002). Once a mathematical model is developed that correlates interoperability

with the performance criteria, the model can be improved through multicriteria identification to a level of adequacy that is deemed acceptable. Statnikov & Matusov (2002) define the experimental value of the vth criterion measured from the prototype as Φ_v^{exp} and the calculated value from the mathematical model as Φ_v^{c} to derive an expression for the adequacy criterion as follows:

$$| \ \Phi_v^{\text{c}} - \Phi_v^{\text{exp}} \ |. \tag{4.1}$$

For our purpose, the adequacy criteria would be a measure of how well correlated the performance criterion determined by the interoperability model is with the actual measurement from the prototype model. Through considerable experimentation with the prototype and an understanding of the nature of the measurement error associated with the performance criterion of the prototype, a maximum value of the adequacy criteria can be determined through expert analysis and in notation presented by Statnikov and Mutusov (2002), written as an inequality:

$$| \ \Phi_v^{\text{c}} - \Phi_v^{\text{exp}} \ | < \varepsilon_v. \tag{4.2}$$

The value of ε_v reflects the maximum value of the adequacy criteria (desired accuracy of correlation between physical and mathematical models). Examining the variables associated with the models that still satisfy the inequality will ensure that alternative representations of the models are identified that may prove useful specifically during efforts to optimize the performance criteria. With a mature mathematical model and high degree of confidence in the correlation between the performance criteria measure predicted by the interoperability model and the performance measure observed from the prototype, the mathematical model may provide a cost effective and rapid means to examine the SoS for potential performance improvement.

b. Use of Adequacy Criteria as Baseline Measure for C4 SoS Performance Assessment

The process required to develop and mature a mathematical model of the SoS also provides greater insight into the associated performance metrics. With an understanding of the nature of the measurement error associated with the prototype, expected values for the performance metrics could be determined and used as a basis for

assessment. The inequality (4.2) could serve as a success criteria that must be satisfied during a SoS assessment. If an assessment results in not meeting the criteria ($|\ \Phi_v^c - \Phi_v^{exp}| \geq \varepsilon_v$), further evaluation of the SoS would be required to determine if a change to the SoS invalidated the mathematical model or if the SoS just failed to perform as expected.

D.   SUMMARY

Modeling the MAGTF C4 SoS is an important facet of the assessment effort. A representative MAGTF C4 SoS that serves as the assessment environment is an abstraction of the actual operational SoS environment and from that perspective can be considered a prototype. This prototype can serve as a means for assessing the overall C2 effectiveness of the SoS if appropriate simulation, stimulation and data collection activities are employed to accommodate both mission thread execution and critical C2 background activities. A complimentary mathematical model would also add value by providing a capability to independently predict SoS performance behavior and gain a better understanding of where and how to best optimize the prototype environment in pursuit of developing a more effective SoS in the operational environment. The i-Score methodology provides a mathematical model that relates an interoperability score to the physical attributes of the SoS, however the interoperability score would be significantly more useful if it can be correlated with performance criteria of the SoS. The use of multicriteria identification may provide a way of modifying the i-Score model (or other mathematical interoperability model) to establish a correlation between the interoperability score and relevant performance criteria. If developed, the mathematical model could provide an efficient means to examine modifications to the SoS in pursuit of performance improvement. Additionally, the use of adequacy criteria determined through the multicriteria identification process may serve as a more reasonable benchmark for evaluating SoS performance during an assessment event by providing an expected value for a performance criteria that accommodates both statistical variance in SoS performance behavior and aspects of known measurement error.

THIS PAGE INTENTIONALLY LEFT BLANK

V. CONCLUSIONS

A. KEY POINTS AND RECOMMENDATIONS

Over a number of years, the Marine Corps Tactical Systems Support Activity has aggressively pursued new and innovative ways to improve efforts to assess the performance of tactical C4 Systems of Systems prior to deployment in an operational environment. In that pursuit, determining how best to approach performance assessments of large-scale, complex SoS has proven a challenge that extends beyond the Marine Corps to a fundamental system of systems engineering challenges shared by acquisition and test organizations and activities throughout the DoD. Selecting key performance criteria, developing methodologies for conducting large-scale SoS assessments and defining more quantitative means for measuring and assessing SoS performance and behavior all serve as a central challenge and the genesis of the initial questions that guided this research:

1. How can large scale C4 System of Systems be tested and evaluated in a manner that reflects performance attributes associated with the System of Systems as a whole?

2. What are the key attributes of a C4 SoS that may serve as the basis for SoS level performance criteria?

3. What are some existing assessment tools and how may they be extended to aid in C4 SoS assessment process?

4. How might multicriteria identification improve or contribute to the Marine Corps' C4 SoS assessment methodology?

For Joint SoS performance assessments, the use of mission-based test threads serve as both a means of stimulating the SoS and a means for assessing performance at the SoS level (capability of the SoS to execute the mission thread from a timeliness and completion percentage rate). The use of a mission-based test thread is also extended to MAGTF C4 SoS assessment efforts, but with a specific C4 focus, other attributes associated with providing a C2 capability are also of interest. Incorporating C2

background activities (situational awareness, position reporting, collaboration, and other DISN services) within the modeled C4 architecture provides an ability to assess aspects of the SoS with respect to providing a C2 capability (capability of the SoS to provide C2 services with regard to bandwidth efficiency and network reliability).

The use of network management and optimization tools that are typically key components of operational C4 SoS have not typically been included in MAGTF C4 SoS assessment events since they do not directly contribute to execution of a mission thread. Adding these components to the assessment environment provides a means to better model QoS and bandwidth availability attributes associated with the SoS and may provide additional insight into and measurement of performance efficiency from a C2 background activity and resource utilization perspective.

In reference to the first two questions that guided this research then, it is recommended that MAGTF C4 SoS assessment efforts include aspects of providing a C2 capability in addition to the ability of the SoS to execute a mission-based test thread as the basis for selection of SoS level performance criteria. This, in concert with addition of network management and optimization tools, will provide the foundation for an assessment with focus on the key attributes of a C4 SoS from a more holistic, SoS performance perspective.

A measure of SoS interoperability also provides a useful means of characterizing a C4 SoS in terms of information exchange attributes that influence both the efficiency and reliability of a SoS. Guided by the third question of this study, three assessment tools were reviewed with each providing a unique approach for evaluating and measuring SoS interoperability. The most promising tools for continued study are the i-Score methodology with an approach that provides a quantitative measure of SoS interoperability, and the DynSAVE software tool that provides a means of quantifying the anomalous behavior and relative efficiency of the SoS. Based on this, demonstrating and further evaluating the improved i-Score methodology is recommended to determine if the higher level of fidelity offered by the improvements add to or enhance the applicability to a C4 SoS assessment event. Demonstrating and evaluating DynSAVE is also recommended to determine whether the structural and behavioral architecture

66

analysis provided by DynSAVE can be extended to provide a measure of efficiency and reliability during a MAGTF C4 SoS assessment. DynSAVE may also illustrate specific data exchange attributes between SoS components that may help determine or improve the resemblance coefficients necessary for the improved i-Score model.

A mathematical model that determines a quantitative value for SoS interoperability like that offered by i-Score may certainly complement a physical model of the SoS like that used for MAGTF C4 SoS assessments. However, the interoperability measure would be considerably more useful if it can be correlated with SoS performance criteria. Guided by the fourth question of this research, multicriteria identification can contribute to the Marine Corps' C4 SoS assessment methodology by providing a means to modify the i-Score model (or other mathematical interoperability model) to establish that correlation. With a mature mathematical model and high degree of confidence in the correlation between the performance criteria measure predicted by the interoperability model and the performance measure observed from the prototype, the mathematical model may provide a cost effective and rapid means to examine the SoS for potential performance improvement. Additionally, the use of adequacy criteria determined through the multicriteria identification process may serve as a more reasonable benchmark for evaluating SoS performance during an assessment event. For those reasons, pursuing development of a C4 SoS mathematical model is highly recommended.

Finally, while SoS assessment is a significant challenge, it is a challenge that is shared across the DoD and throughout the systems engineering community. Continued involvement in Joint DoD efforts such as JMETC provide the Marine Corps with a unique opportunity to refine assessment methodologies, examine new tools and techniques and leverage expertise and lessons learned through continued collaboration within this growing community of interest. Engagement is not just a good idea, but is essential to improve and mature the Marine Corps' engineering and test effort as applied to current and future generations of the MAGTF C4 SoS.

B.   AREAS TO CONDUCT FURTHER RESEARCH

A number of areas discussed in this study warrant further examination. First, demonstration and evaluation of the improved i-Score methodology may be beneficial to determine if the improved methodology shows potential for greater applicability to C4 SoS assessments. Second, demonstration of the DynSAVE assessment tool during a C4 SoS assessment would provide an opportunity to examine capabilities and limitations of this tool in a controlled environment.   Third, further study towards development and use of a mathematical model for C4 SoS assessment and optimization may provide considerable benefit. While extensive experimentation through a physical model of the C4 SoS to develop and improve the mathematical model is necessary, application of simulation and stimulation tools and virtualization technology may help expedite this effort. Finally, virtualization technology may serve as a fruitful area of study from two perspectives: using a virtual model of the SoS as the basis for an assessment, and determining appropriate tools and analysis methodologies for assessing C4 SoS that employ virtualization technology as part of their inherent architecture.

1.   C4 SoS Assessment Using a Virtual Model

The use of virtualization technology to model the C4 SoS offers considerable advantage by reducing the physical resources needed to create the C4 SoS assessment environment. The benefits of using a virtual model to validate assessment procedures has been demonstrated, but even greater value would be derived if a virtual model of the C4 SoS could be extended to serve as the actual assessment environment. Because the virtual model presents another degree of abstraction from the physical model, experimentation and analysis is necessary to determine where and how variances between the virtual and physical models manifest in terms of SoS performance measures.

2.   Assessment Tools and Analysis Concepts for C4 SoS Analysis in Virtual SoS Analysis Environment

A number of Marine Corps' Systems of Systems, including the COC, intend to employ virtualization technology within their architectures. Virtualization of network components (servers and switches), as well as various C2 client components, will change

the performance and behavior attributes of the SoS. Additional research is needed to determine whether current assessment tools, techniques and performance criteria are sufficient to conduct an assessment of a C4 SoS that employs virtualization technology or if additional or new tools are necessary.

THIS PAGE INTENTIONALLY LEFT BLANK

LIST OF REFERENCES

Acosta, J., Hoesly, S., Huseth, S., Krider, S., Lamb, J., Martin, C., et al. (2007). *Architecting joint command and control system of systems capability certifications*. Capstone Project Technical Report, Naval Postgraduate School, Monterey, CA.

Chairman of the Joint Chiefs of Staff (CJCS). (2007, May 1). *Joint Capabilities Integration and Development System* (CJCS Instruction 3170.01F). Washington, DC: Pentagon.

Chief Systems Engineer, Assistant Secretary of the Navy for Research, Development, & Acquisition (ASN RDA). (2010). *Mission area "systems of systems" systems engineering guidebook version 3.x*. Unpublished Draft. Washington Navy Yard, DC.

Clark, J. (2009). *System of systems engineering and family of systems engineering from a standards, V-model, and dual-V model perspective*. Retrieved April 25, 2010, from http://www.incose.org/hra/past_events/ IEEE2009_SoSEandFoSE_JOC_090223.pdf

Cloninger, J. (2009). Marine corps cyberspace in support of MAGTF C2: By many a Marine, with a single vision. *Military Perspectives on Cyberpower*, 96–112. Center for Technology and National Security Policy at the National Defense University, Washington, DC. Retrieved May 5, 2010, from http://www.ndu.edu/CTNSP/pubs/Military_Perspectives_Cyberpower_2009.pdf

Defense Acquisition University (DAU). (2010, March 19). *Defense acquisition guidebook (DAG)*. Fort Belvoir, VA: Author.

Ferguson, C. (2009, October 28). *Lowering technical risk by improving distributed T&E capabilities*. Presented at the 12th Annual NDIA Systems Engineering Conference 2009, San Diego, CA. Retrieved May 3, 2010, from http://www.dtic.mil/ndia/2009systemengr/8814WednesdayTrack4Ferguson.pdf

Fiebrandt, M., & Dryer, D. (2009, January 13). *Capability test design and analysis*. Presented at the International Test & Evaluation LVC Conference. Retrieved May 3, 2010, from http://www.itea-wsmr.org/ITEA%20Papers%20%20Presentations/2009%20ITEA%20Papers%20 and%20Presentations/LVC_MFiebrandt_DDryer_JTEMCapabilityTestDsg_slides _Jan%2009.pdf

Ford, T., Colombi, J., Graham, S., & Jacques, D. (2006). A survey on interoperability measurement. *Submission to the Call for Papers: 12th ICCRTS "Adapting C2 to the 21st Century."* Retrieved 22 May, 2010, from http://www.dodccrp.org/events/12th_ICCRTS/CD/html/papers/096.pdf

Ford, T., Colombi, J., Graham, S., & Jacques, D. (2007). The interoperability score. *Proceedings from the Conference on Systems Engineering Research 2007.* Stevens Institute of Technology Campus, Hoboken, New Jersey. Retrieved May 3, 2010, from http://www.stevens-tech.edu/ses/seem/fileadmin/seem/Proceedings_PDF/27.pdf

Ford, T., Colombi, J., Graham, S., & Jacques, D. (2008). Measuring system interoperability (An *i-Score* Improvement). *Proceedings from the Conference on Systems Engineering Research 2008.* Los Angeles, CA. Retrieved May 3, 2010, from http://cser.lboro.ac.uk/CSER08/pdfs/Paper%20221.pdf

Ganesan, D., Lindvall, M., Bartholomew, M., Blau, M., McComas, D. & Cammarata, G. (2008). Analyzing the Core Flight Software (CFS) with SAVE. Fraunhofer USA, Inc (Presentation). Retrieved June 4, 2010, from http://www.flightsoftware.org/files/FSW08_**Ganesan**.ppt

Hutchison, S., Lorenzo, M., & Bryan, D. (2009, January-February). Capability test methodology and joint battlespace dynamic deconfliction (Electronic Version). *Defense AT&L*, 30–33.

Huynh, T. and Osmundson, J. (2006). A model for assessing the performance of interoperable, complex systems. *Proceedings of the 2006 Conference on Systems Engineering Research.* Stevens Institute of Technology, Hoboken, NJ, paper 167. Retrieved May 22, 2010, from http://sse.stevens.edu/fileadmin/cser/2006/papers/127-Huynh-Performance Assessment Model.pdf

Ingber, L., Fujio, H., & Wehner, M. (2001). *Mathematical comparison of combat computer models to exercise data*. Unpublished paper, Naval Postgraduate School, Monterey, CA.

JITC. (2009, September 21). Joint C4ISR interoperability Test & Evaluation (T&E) Capability (InterTEC). Retrieved May 3, 2010, from http://jitc.fhu.disa.mil/intertec/index.html

Joint Chiefs of Staff. (2009). Department of Defense Dictionary of Military and Associated Terms, 12 April 2001 (As Amended Through 31 October 2009). Retrieved May 22, 2010, from http://www.dtic.mil/doctrine/dod_dictionary/

Lawver, L. (2007, June 19*). Interoperability Quotient process "IQ" overview*. Lecture presented for the JMETC User Group Conference, Dulles VA.

LeSueru, K., Millich, S., & Stokes, M. (2009). Lessons learned: Joint Battlespace Dynamic Deconfliction (JBD2) distributed test event. ITEA-WSMR. Retrieved May 3, 2010, from http://www.itea-wsmr.org/ITEA%20Papers%20%20Presentations/2009%20ITEA%20Papers%20and%20Presentations/LVC_KLeSueur_JBD2%20JTEM_paper_Jan09.pdf

Lindvall, M., Ackermann, C., Stratton, W., Sibol, D., Ray, A., et al. (2007). *Using sequence diagrams to detect communication problems between systems*. IEEEAC Paper #1099, Version 4, Updated December 14, 2007.

Lockhart, R. & Ferguson C. (2008). Joint Mission Environment Test Capability (JMETC) (Electronic version). *ITEA Journal 2008*, 29: 160–166.

Lorenzo, M. (2009, April 17). *Action Officer's Handbook for Testing in a Joint Environment*. Office of the Secretary of Defense, Joint Test & Evaluation, Joint Test and Evaluation Methodology, Washington, DC.

Marine Corps Tactical Systems Support Activity. (2009, January 14). MAGTF C4I Capability Certification Test (MC3T) 08-01 Test Report Version 1.0 (CM# SI-312).

Morris, E., Levine, L., Meyers, C., Place, P. & Palakosh, D. (2004, April). *System of Systems Interoperability (SOSI): final report* (CMU/SEI-2004-TR-004). Pittsburgh, PA: Carnegie Mellon Software Engineering Institute.

Office of the Deputy Under Secretary of Defense for Acquisition and Technology, Systems and Software Engineering. (2008). *Systems Engineering Guide for Systems of Systems*, Version 1.0. Washington, DC: ODUSD (A&T) SSE.

Phillips, D. (2008). *Mathematical modeling and optimal control of battlefield information flow*. Doctoral dissertation, Naval Postgraduate School, Monterey, CA.

PM MAGTF C2. (2009, June). *Systems System/Subsystem Specification (SSS) for the Combat Operations Center (COC)* AN/TSQ-239 (V), Model G. Marine Corps Systems Command, Quantico, VA.

SIAT. (2010, April 20). Marine Corps Systems Command. Retrieved April 20, 2010, from http://www.marcorsyscom.usmc.mil/syscomorg/default.aspx?PG=10

Sjoberg, E. (2008). *Application of i-Score to MC3 08-01*. MCTSSA, Camp Pendleton CA. Unpublished white paper.

Statnikov, R., Bordetsky, A. & Statnikov A. (2008). *The best solutions: How and where to seek them?* Unpublished preliminary draft, Naval Postgraduate School, Monterey, CA.

Statnikov, R. & Matusov, J. (2002). *Multicriteria analysis in engineering*. Netherlands: Kluwer Academic Publishers.

Stratton, W., Sibol, D., Lindvall, M., Ackermann, C. & Godfrey, S. (2009). *Developing an approach for analyzing and verifying system communication*. IEEEAC Paper #1275, Version 5, Updated 2009, January 22.

Stratton, W., Sibol, D., Lindvall, M., & Costa, P. (2006, December). *Technology infusion of SAVE into the ground software development process for NASA missions at JHU/APL*. IEEEAC Paper #1123, Version 7, Updated 2006, December 5.

U.S. Marine Corps. (2001). *Marine Corps Operations* (MCDP 1-0). Washington, DC: Author.

Walters, C. (2010, March). JTEM-T establishes metrics working group. *JT&E Newsletter*, 11(1). Retrieved May 7, 2010, from http://www.jte.osd.mil/docs/newsletterarchives/JTE-NewsletterMar10.pdf

Zapata, E. (2010, July). Combat operations center OV-1 [Graphic]. Operational Architecture Branch, Headquarters Marine Corps, Combat Development and Integration.

Zapata, E. (2010, July). Common aviation command and control system OV-1 [Graphic]. Operational Architecture Branch, Headquarters Marine Corps, Combat Development and Integration.

INITIAL DISTRIBUTION LIST

1. Defense Technical Information Center
   Ft. Belvoir, Virginia

2. Dudley Knox Library
   Naval Postgraduate School
   Monterey, California

3. Professor Gregory Miller
   Naval Postgraduate School
   Monterey, California

4. Dr. David Rathgeber
   Marine Corps Tactical Systems Support Activity
   Camp Pendleton, California